U.S. AIR FORCE Project RAND

AIR DEFENSE STUDY

October 15, 1951

R-227 (ABRIDGED)

The RAND Corporation
SANTA MONICA · CALIFORNIA

Subject: R-227 Abridged Version

Enclosed is a copy of an abridged version of R-227, "Air Defense Study (U)." This abridged version is unclassified and approved for public release.

Please let me know if you have any questions or if I can be of further assistance.

Sincerely,

Angela Wong

Angela Wong
RAND Publications Cataloger
Enclosure (1)

Errata for RAND Report R-227, *Air Defense Study*

p. 75, line 4	*should read*: obtain for 50-KT bombs:
p. 117, Fig. 34	*bottom of load factor scale should read* 1.0
p. 128, Fig. 35	*change kill potentials from* 580 *to* 290 *and from* 540 *to* 270
p. 132, Fig. 41	*interchange the labels* 1 salvo *and* 3 salvos *on the green curves*
p. 134, Fig. 42	*add a green line in the key opposite* MX-904 missiles
p. 156, line 2	*add*: The values given in Table 9 are for ideal fuzing of the 318-lb rockets. For intermediate fuzing (see p. 153), the values of P_{KB} should be multiplied by 0.94 (variable time-of-flight) or 0.91 (fixed time-of-flight) and the values of P_{KMB} by 0.82.
p. 160, par. 2, line 11	*delete* or, *so that line reads*: attacks is greater than the mean time by an amount equal to twice the
p. 248, par. 3, line 4	*add*: Radar echoing areas assumed for these graphs were 100 m^2 for the TU-4, 40 m^2 for the Stalin, and 1 m^2 for the air-to-surface missile.
p. 249, Table 29	*Beam width of the AN/APS-20B, 17-ft dish, should read* 1.5 *instead of* .5
p. 304, par. 2	*the definition of* R_c *should read*: R_c is the interceptor combat radius, equal to $(x + y)/2$ of Fig. 90,
p. 331, Fig. 101	*in the key at lower right, the height of the first pulse should be labeled* 1

* * *

NOTE ON COSTS

The costs used in RAND's Air Defense Study were usually based on data gathered in 1949 and 1950, since analysis began in late 1950. In addition to the general inflationary trend since then, several other factors have acted to increase manufacturing costs of aircraft and missiles above the level cited in R-227. First, nearly every airplane and missile is now being made much more complex than similar World War II items, and usually more complex than it needs to be to do the job envisaged in the study. Secondly, costs of missiles, aircraft, and auxiliaries, especially of electronic equipment, have increased substantially over the costs of nearly identical items of several years ago, even after general inflation is taken into account. One reason for this is the rapid expansion of the industry. Thirdly, most of the RAND data came from manufacturers' estimates of production costs which accompanied bid proposals. These usually proved to be low for the reasons just mentioned and because of the optimism expected in this source. While some allowances were made for these factors, they did not prove sufficient. If users of the study try to take these factors into account, it is suggested that this be done by adjusting the dollar label of a certain defense level (corresponding to a given number of squadrons, for example) and not by making piecemeal adjustments of component costs, unless the latter can be done extensively enough to ensure consistent treatment.

FOREWORD

Defense against air attack, as a full-scale military operation, first came into being during the Battle of Britain. Its importance to every nation was increased by the advent of the atomic bomb in 1945. Following the Soviet atomic explosion in September, 1949, the United States air defense effort was sharply intensified. This greater emphasis has resulted in a significant change in the portion of Air Force budget allocated to air defense, both for development of new equipments and for the production of operational weapon systems. In terms of Air Force research and development funds, the fraction allocated to air defense increased from about 10 per cent in the Fiscal 1950 budget to 25 per cent in the Fiscal 1952 budget. In absolute terms, the increase is even greater, because the Korean war has resulted in very much larger military budgets and larger allocations of funds to research and development efforts.

Although larger and larger amounts of money are being spent for air defense, this is but one of the Air Force responsibilities. An important objective of air defense planning therefore must be to minimize the cost of an acceptable level of defense capability. When Maj. Gen. Gordon P. Saville (USAF ret.) was Commanding General of Air Defense Command, he frequently sketched a "pie" chart for visitors. This chart showed a slice for air defense, and slices for the other Air Force missions. He regarded efficient planning, and keeping the air defense budget to a minimum for a given capability, as being one of the important responsibilities of his position. This has also been one of the prime objectives of the RAND Air Defense Study—to seek an air defense system capable of doing the best possible job for a given budget and to key air defense planning to the operational requirements of the expected military situation.

An inherent feature of any air defense system is the complex network of data-gathering and communications equipments. It is necessary to process a large quantity of data rapidly so that decisions can be made and weapons controlled with a minimum of confusion. It is characteristic of defense that it must stand ready to meet a variety of eventualities. The offense can prepare for months to carry out a specific operation which will concentrate its forces at a particular time and place. The defense, on the other hand, must marshal forces rapidly to meet a developing situation about which very little is known in advance. In the Battle of Britain it was the new science of radar that permitted

a numerically inferior force to do an efficient job in meeting the German Air Force at a time and place selected by the Germans. In addition, the decisive factor in the next air war may be the ability to take advantage of every enemy mistake. To do this our weapons must have great flexibility and our system of intercommunication must be highly efficient.

Several years ago RAND realized that the need for sound advice in choosing preferred weapons and tactics for air defense had been greatly heightened by the course of events described above. In July, 1950, a fairly large number of technical personnel, representing a wide variety of specialized fields, were assigned to the task of analyzing the air defense problem. Continuous liaison between RAND and USAF commands and agencies and industrial contractors has been maintained to ensure that the final analysis would contain recent and reliable data. Through these means, and through the publication of research memoranda over the past year, some of the findings of the study have been made known. In some cases work has already been initiated in the directions indicated by the study. A primary set of recommendations, covering most of the conclusions of Chap. 2 of this report, was submitted to the Air Staff in October, 1951.

Although the RAND Air Defense Study concentrated its attention on air defense in the future, present United States defense capabilities were taken as a starting point. The deficiencies of our defense system are well known, and with a growing Soviet A-weapon capability, these may become very serious before they can be corrected. To alleviate this situation, new devices and tactics must be developed and made to work effectively.

Unexpected advances in technology may or may not pay off in actual operations. On the other hand, RAND feels that a careful and comprehensive analysis of the problem may contribute to the understanding of the actions needed to obtain an effective defense system. The study has indicated that as the years go by it will become increasingly difficult to ensure a high probability of stopping enemy bombers. The study indicates the methods of attaining and maintaining this capability and recommends a concentration of effort to make this possible.

ACKNOWLEDGMENTS

The Air Defense Study described in this report is the work of a large number of technical personnel at RAND, aided in many essential respects by outside organizations. Much valuable and pertinent information furnished by outside agencies was obtained informally, and it has not usually been possible to indicate these sources by footnote references to published reports.

The entire project was directed by E. J. Barlow, with administrative and technical support from RAND's Electronics Division. Barlow was assisted in most of the planning and technical guidance by a team consisting of J. F. Digby, W. B. Graham, R. W. Krueger, J. D. Mallett, C. V. Sturdevant, and W. B. White.

Within RAND, the number of people who participated is far too great to permit a complete listing. In the partial list that follows, an attempt has been made to name those who devoted full time to the study during its most productive stages, whose contributions were mainly to the over-all study rather than to its more specialized aspects, and who participated in discussions which helped to formulate the program of work. Credit for much of the specialized work lies with the authors of the research memoranda listed in Appendix II; not all of these authors are included below.

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W. B. White

The work of synthesizing the component studies, and relating the equipment studies to the possible United States bombing targets, was accomplished by a group which included:

R. Davies	R. C. Emerson
R. H. Dishington	P. C. Keith

E. Pond

CONTENTS

Appendix II and all classified references have been deleted

CHAPTER 1

NATURE AND SCOPE OF THE STUDY

RAND has investigated the air defense of the United States from the earliest date at which a serious enemy threat is believed to exist until that time in the future when it becomes impossible to predict the scientific progress in either our own or the enemy's weapons with any degree of confidence.

The earliest date at which the Soviet strategic air capability can do serious damage to this country is estimated to be about 1953. Also, the earliest date at which the present Air Force program for the radar network and interceptor squadrons will be in full operation is late 1952 or 1953. For these reasons, 1953 was taken as the starting date for the analysis. Since 1960 is about as far into the future as it is possible to make reasonable predictions about probable new defense and offense weapons, it was taken as the closing date of the study. Because of this extended period of time, many offense and defense weapons were investigated. Passive defense was not considered in this study.

Specific estimates of our active air defense capability were made for the dates 1953, 1955, 1957, and 1959.

Soviet capabilities in atomic bomb production and in production and operation of strategic aircraft and guided missiles were estimated for the time span of the analysis. In addition, the probable enemy attack routes and tactics were considered. The effect on the conclusions of the study of possible Soviet capabilities with BW, CW, or RW weapons was also estimated. One of the results of this investigation of the enemy threat was to demonstrate that the enemy might well use a very-low-altitude attack. The defense against this low-altitude attack is one of the central themes of the present study.

The specific targets in the Zone of the Interior of the United States which should be defended by active air defenses were estimated. These consist of large-population concentrations, selected war industries, and counter-air-force installations. Lists and maps of these targets were made. These maps of the target system were of use throughout the study in determining preferred weapon deployment, enemy attack routes, etc.

Studies were made of the individual defense weapons which may be available in operational quantities at various times during this period. Both the

technical feasibility of these weapons and the present nature of the research and development effort leading to them have been considered. This part of the study permits an evaluation of the relative feasibility of various kinds of weapons. Specific suggestions are made about the most promising lines to be pursued in several research and development programs, particularly in the fields of missile guidance, missile seekers, low-altitude ground radars, and data-handling equipment in the low-altitude radar network.

The vulnerability of defense weapons to electronic countermeasures (ECM) was estimated, and the steps to be taken in the initial design of these new weapons to make them as invulnerable as possible to ECM are enumerated.

Some of the weapons considered, particularly in the early years studied, already have their basic design characteristics fixed. However, in the later years covered by this study, many of the weapons considered are still in the very preliminary design stage, so that their design characteristics are not yet firm. In these cases, studies were made of the preferred characteristics of the weapons. In particular, the next generation of manned interceptors was studied and preferred design characteristics are recommended. In addition, a class of large air-to-air missiles was studied in the same way. The designs of an advanced type of local-defense surface-to-air missile and an advanced area-defense surface-to-air missile were examined in detail. Finally, preferred characteristics are described for a class of small radars, called Muldar, to give low-altitude coverage.

The preferred deployment of radar systems and defense weapons—for both area and local defense—has been suggested, taking into consideration an actual target system, properties of the defense weapons, and enemy offense capabilities in terms of weapon range, attack routes, etc.

Estimates were made of the costs of maintaining the defense weapons studied in operational use in specific quantities. These cost studies have a wider scope than those commonly made in that they consider as many as possible of the dollar costs associated with a weapon program—the purchase of the equipment, maintenance of the equipment, salaries of the operating personnel, training, installation, etc. This type of costing provides a more realistic measure of the over-all effort that goes into a weapon-development program and sheds new light on the relative importance of various changes which could be made in weapon design.

A numerical estimate was made of the attrition which each of these kinds of weapons, or combinations of these weapons, could inflict on the expected enemy

force. A similar estimate was made of the performance of detection networks. The numerical part of the study makes use of theoretical evaluations of weapon performance and of estimated operational degradation of such performance and considers the individual weapons in an operational framework. The present analysis of the air defense of the United States is unusual in that it attempts a quantitative synthesis of the relative capabilities of defense weapons and radar networks within a framework which includes a real target system, specific enemy threats, etc. Results of this study are couched in terms of numerical estimates of the attrition which may be inflicted on the enemy and estimates of the physical damage which may be done to our targets by hypothetical enemy attacks at various times during the present decade, thus giving a measure of our ability to defend the United States as the years go by. The analysis examined the effect of varying the combat radius of area-defense weapons and the relative effectiveness of area- and local-defense weapons. In addition, numerical results show the interaction between the properties and the effectiveness of defense weapons on the one hand and the extent and cost of the coverage provided by the detection network on the other.

Numerical studies such as that described above are necessarily unable to predict accurately the performance of future weapons in future and unknown military situations and so these numerical results must be interpreted carefully. A discussion of this point is included in the report (see Chap. 3, in particular).

From the results of the foregoing studies, the preferred weapons and weapon combinations which would give the maximum air defense capability, year by year, are estimated.

In conclusion, the basic weaknesses of our air defense system, year by year, are pointed out, and important research and development programs necessary to obviate these weaknesses are suggested.

CHAPTER 2

CONCLUSIONS AND RECOMMENDATIONS

The results of the Air Defense Study are presented here against a background of the presently programmed air defense system for 1952–1953, and against estimated enemy threats year by year.

The deficiencies of this system are pointed out, and the procurement or research and development programs necessary to alleviate these deficiencies and to prepare for the enemy threats of later years are discussed.

In most cases of new development there already are research and development programs aimed at correcting these deficiencies; in a few cases new programs are suggested.

Plans for the air defense system are in a constant state of flux, and it is difficult, if not impossible, for a study of this scope to keep abreast of the latest changes. Therefore, as a point of reference, the official programmed air defense system discussed here is taken to be the following:

- *Radar network* to consist of 104 sites for fixed land-based radars, 75 in the United States and 29 in Canada, located as shown on the map (Fig. 1), plus 16 mobile radars. The fixed sites use 34 AN/CPS-6B radars and 70 AN/FPS-3–AN/FPS-6 combinations. There are no radars, either picket ship or airborne early warning (AEW), for over-water coverage. Data handling is by voice-telling over telephone lines, manual plotting boards, manual intercept controlling, etc.

- *Interceptor force* to consist of 45 squadrons of a mixture of F-86D,[1] F-94C, and F-89D aircraft armed with 2.75-in. folding-fin air rockets (FFAR) and collision-course computers. These are all-weather interceptors having the AN/APG-37 family of radar. The armament load programmed now is 24 rockets in the case of the F-86D and F-94C, and 104 rockets in the case of the F-89D.

[1] Whenever the name of an actual or proposed weapon is used in this report, it is implied that the manufacturer's detailed design characteristics at the date of the study have been taken and that independent estimates of the expected performance have been made by RAND. In most instances these estimates correspond closely to those made by the manufacturer.

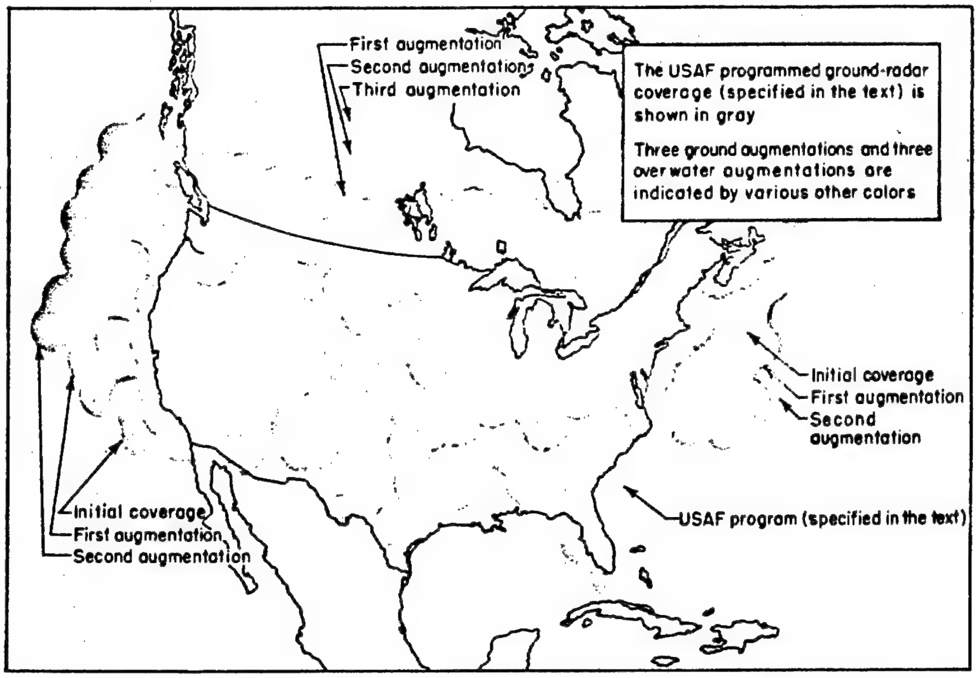


Fig. 1—Radar network and the augmentations considered in the study

- *Local-defense force* to consist of 55 battalions equipped with 90-mm and 120-mm antiaircraft batteries and 9 battalions equipped with 75-mm Skysweeper.

New and improved weapons and radars are estimated to be available in later years. The availability dates[2] are shown in Figs. 2, 3, and 4. In addition, the actual numbers of weapons and radars employed may be greatly changed in later periods. In the study, many different quantities of weapons and radars were considered.

The effectiveness of an air defense system depends on the threat it must meet. For the 1953 period, a detailed picture of this threat has been built up by consideration of intelligence information, basic technological possibilities

[2] These are the dates when the weapons are estimated to reach full operational strength. They may begin to appear one to two years earlier. In many cases two essentially competing systems reach availability within one or two years of each other in these charts. In such cases, it is *not* implied that both should be developed and produced, *nor* is it implied that if an improved system becomes available before a previous one has had a few years of service, it should necessarily replace it. Furthermore, these are estimates of the earliest dates at which these weapons are likely to appear if the programs continue as anticipated. Obviously some programs may run into serious technical difficulties and be delayed or stopped.

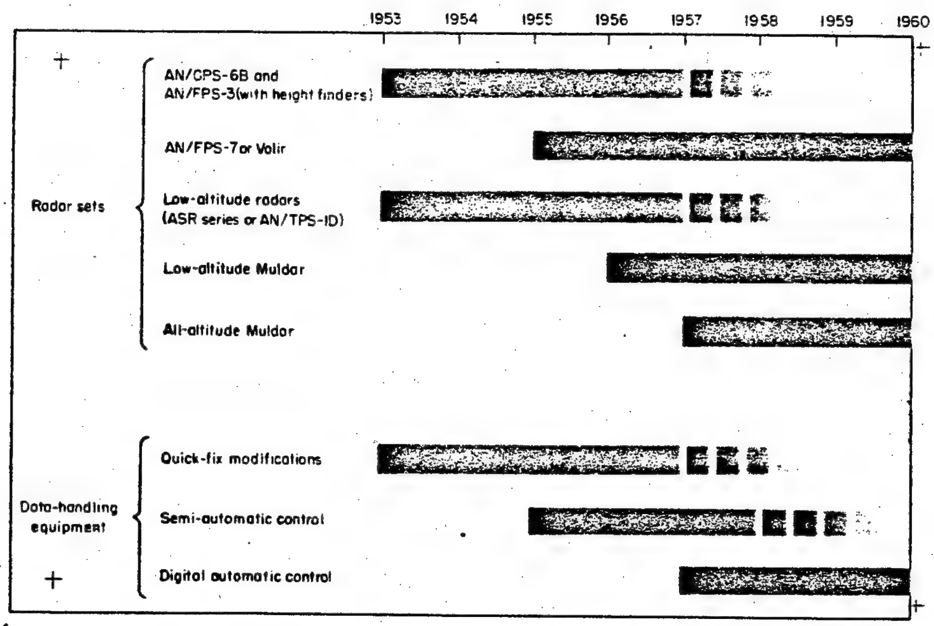


Fig. 2—Availability dates of ground radars and data-handling equipment

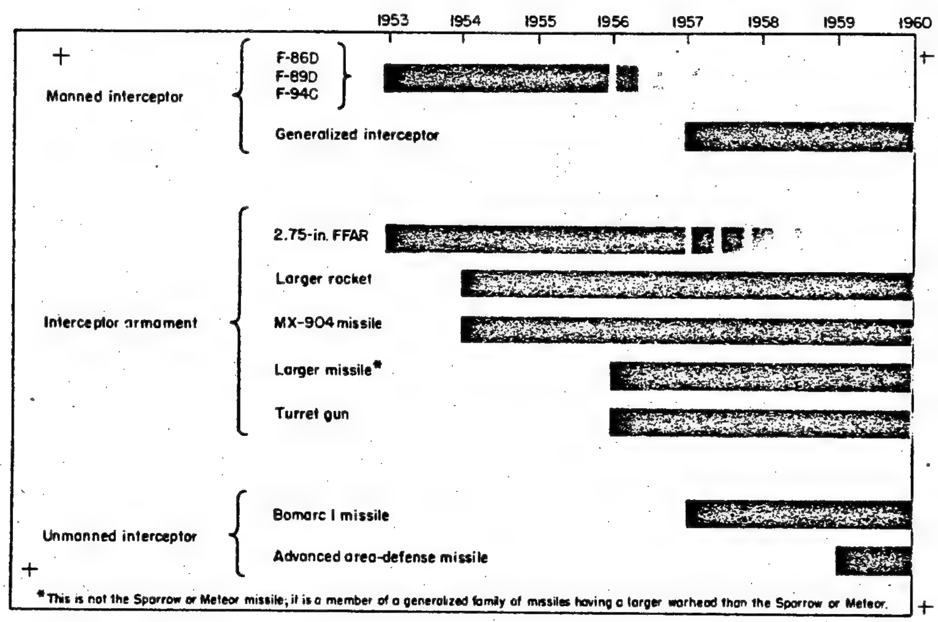


Fig. 3—Availability dates of interceptors, interceptor armaments, and area-defense missiles

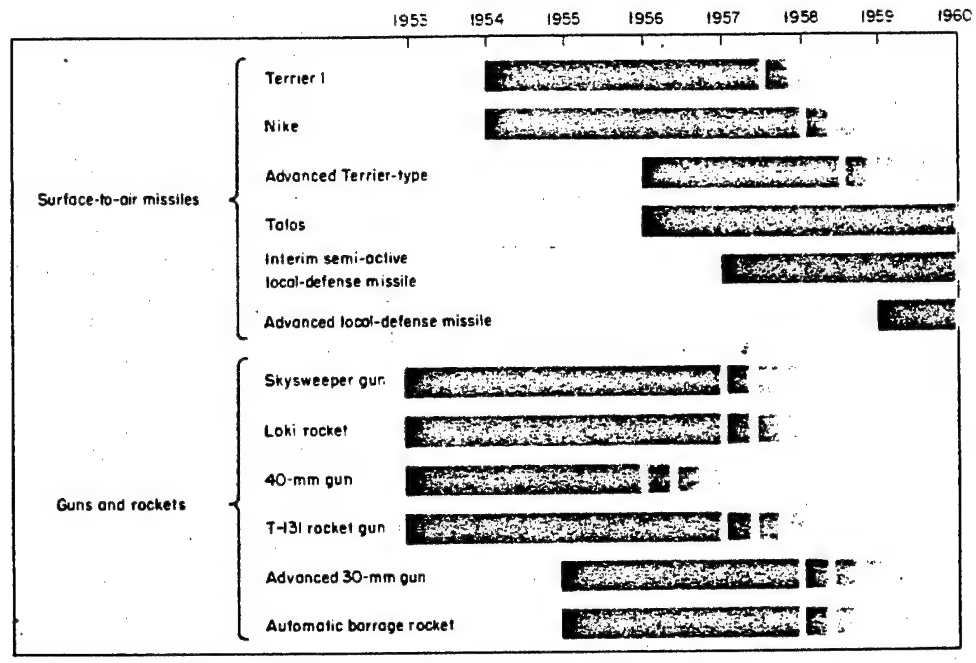


Fig. 4—Availability dates of local-defense weapons

and limitations, geographical properties of the United States relative to possible attack bases, estimates of the motivation of the enemy, etc. This estimate of the enemy attack has been used to evaluate the capabilities and deficiencies of our air defense system. Several variations in this attack have also been considered, and in the years after 1953, allowance has been made for changes in weapons and tactics. For the 1953 period, the threat has been developed as follows:

- The enemy would be the Soviet Union.
- The weapon would probably be the atomic bomb. The enemy is estimated to have a rapidly increasing capability with this weapon and through its use could produce definite physical destruction of part of our war-making capability. There is some indication that such destruction would be favored by Soviet planners over some more indirect form of attack. It appears that the use of BW, CW, or RW weapons would not materially change the conclusions of this study about our active air defense system.
- The number of bombs which might be allocated to an attack on this country was obtained by estimating the size of the Soviet stockpile

of atomic bombs and then allowing for some to be allocated to an attack against England or Western Europe and some for reserve. This left about 100 bombs as the estimated number which might be allocated to an attack on the United States in 1953. In later years this number would reach several hundred.

- It is estimated that in 1953 the carrier would be the TU-4 bomber. It seems likely that there could be a large operational force of these aircraft. In later years more advanced bomber types are possible and aircraft similar to the B-52 and B-47 (with turboprop modification) have been considered. The recent appearance of a new Russian bomber, the Type 31, does not change the situation, as its estimated performance is comparable with that of the TU-4 except for its greater range.
- The number of TU-4 aircraft which might be allocated to an attack on this country in 1953 was estimated to range from a minimum of about 100 to a maximum of about 500. This estimate was based on considerations of tactics and logistics as well as on estimates of the size of the Soviet long-range air force.
- The number of enemy strikes and the weight of each strike were considered, and it was concluded that a likely pattern would be an attack in one massive strike, perhaps followed by a smaller clean-up strike. Other strike patterns were considered, however.
- Because of the range limitations of the TU-4 bombers, these missions would be either one-way unrefueled missions or round-trip once- or twice-refueled missions. One-way unrefueled missions are considered most likely in 1953 because they are simpler to accomplish and permit a maximum weight of attack. In later years round-trip missions, perhaps with the Type 31 bomber, are to be expected.
- Approximately one-third of the United States targets considered as possible Soviet choices lie within a few hundred miles of our seacoasts, and many other targets can be reached best by a seacoast approach; hence, it is estimated that a large fraction of the attacking force may approach by overwater routes.
- Various altitudes of enemy attack have been considered, and it is estimated that the Soviet Union has the capability for staging either a high- or a low-altitude attack with effective utilization of its atomic

bombs in either case. Because of the weaknesses of our radar network and interceptor force against low-altitude attack, and because of the small number of low-altitude local-defense weapons programmed, it is concluded that the most likely attack would be a low-altitude one.

- With the number of atomic bombs estimated for 1953, the Soviet Union has considerable freedom in its choice of targets. This allows considerable latitude in the routes chosen and permits attack on alternative targets in case of bad weather.

In the absence of *any* air defense, the 100 bombs estimated for 1953, even considering operational losses and aborts, could do severe damage to our economy. For example, if directed against strategic war industries, they could effectively destroy the critical facilities of any one of a series of target systems, such as our petroleum refineries or steel mills. If directed against our large cities, they could destroy 5 to 10 million homes, with an attendant large number of casualties and fatalities.

In later years, the Soviet threat will become even more serious because it is estimated that the number of bombs they could attempt to deliver will increase to several hundred. Higher-performance bombers may be available, as may air-to-surface missiles of various capabilities ranging from subsonic missiles, having 5- to 10-mile[3] range, to supersonic missiles, having a range of several hundred miles. The estimated availability dates for these various offensive threats are shown in Fig. 5. The turboprop bomber mentioned above is called the "Volga" and the high-performance bomber is called the "Lenin." In later chapters, the B-52 type is referred to as the "Stalin."

The target system employed in the present study is presented in Fig. 6.

Against this background, the most immediate deficiencies in our air defense capability appear to be the following:

1. Inadequate radar coverage and data-handling facilities.
2. Inadequate identification procedures and rules of engagement.
3. Inadequate defense against low-altitude attack.

As time goes on and the enemy capability increases, other deficiencies will become increasingly important. They are:

4. Inadequate total defense strength.

[3] Nautical miles (6080 ft) are used throughout this report unless otherwise stated.

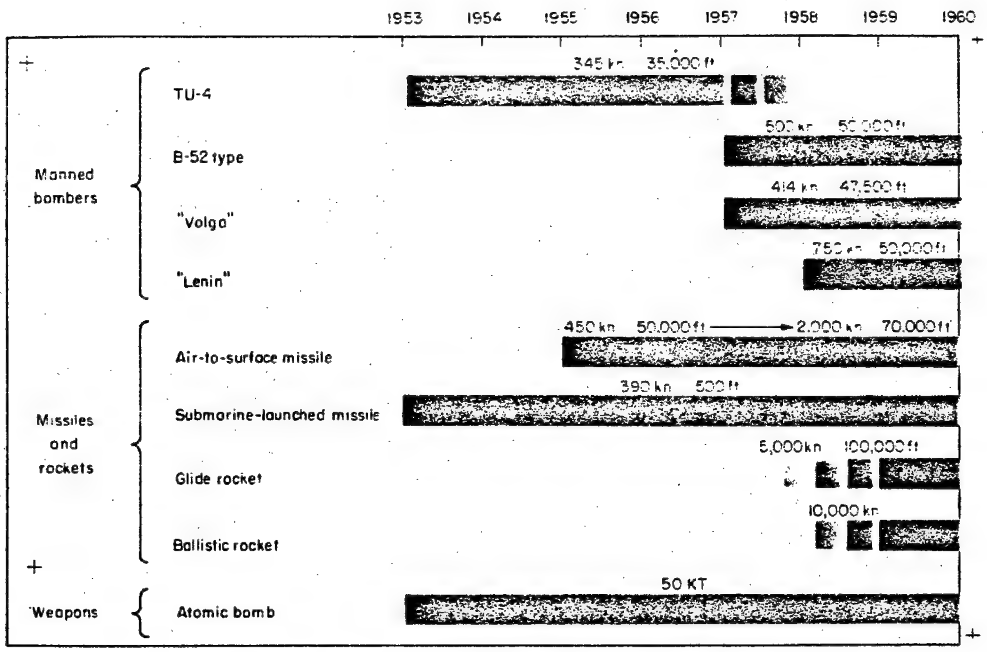


Fig. 5—Availability dates of enemy offense equipment

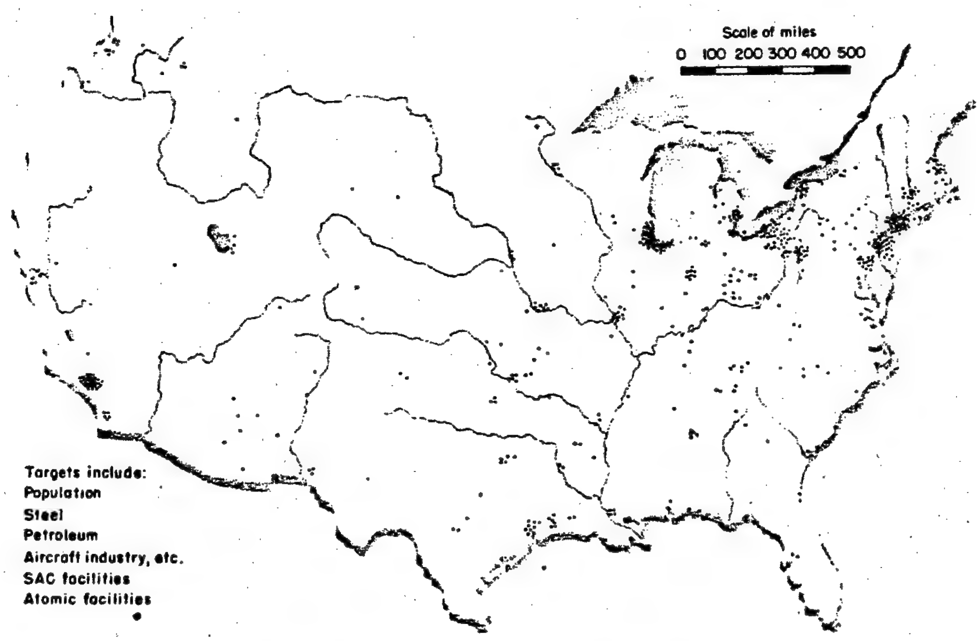


Fig. 6—United States target system

5. Inadequate defense-weapon effectiveness against advanced types of enemy threats.

These deficiencies are discussed below.

I. Inadequate Radar Coverage and Data-Handling Facilities

The presently programmed[4] ground-based radar network does not give sufficient radar coverage against enemy bombers approaching the United States by overwater routes. A study has been made of the relative advantages of picket ships and of various types of airborne-early-warning (AEW) aircraft to provide this coverage. It was concluded that coverage could best be supplied by a combination of picket ships and AEW aircraft. The picket ships would serve as identification check points and as stations for the transmission and handling of data, in addition to supplying high-altitude radar coverage. The AEW aircraft would supply low-altitude coverage and flexible coverage which could be deployed farther out to sea as needed. The preferred type of AEW aircraft was the PO-2W equipped with a 17-ft search antenna.

Various amounts of outward extension of our radar coverage were investigated, as shown in Fig. 1. Extensions both up into Canada and out over the oceans were studied. Some of the factors considered in selecting a preferred amount of radar coverage were:

- Time to perform the identification, using several methods as checks.
- Time for deployment of interceptors to defend targets other than those they are nearest.
- The statistical nature of radar aircraft detection ranges.
- The geographic relationships of interceptor bases, radar sites, and target complexes.
- The combat time required under all-weather conditions to ensure a high probability that interceptors will discharge their armament load effectively against bomber targets.
- The cost of various radar-coverage extensions.
- The rate at which interceptors would be scrambled from their bases.

The conclusion of this part of the study is that the preferred amount of overwater coverage, at least off the east coast, is that corresponding to two

[4] Again this is the official program described on page 5.

lines of picket ships, for example—one line about 150 miles off shore, and the other about 300 miles off shore. The preferred way is to get this coverage with a combination of picket ships and AEW aircraft, i.e., to have one line of picket ships about 150 miles off shore and a line of continuously patrolling AEW aircraft about 250 miles off shore. This will leave a gap in the coverage against low-altitude bombers, so a few additional AEW aircraft should be based along the coast ready to take off when the outlying AEW patrol alerts the radar network. Because these additional AEW aircraft are not required to be on continuous patrol, they cause a relatively small increase in the total AEW force requirements. The total force requirements for such overwater coverage (including both coasts) are estimated to be about 25 picket ships and 50 AEW aircraft.

As far as overland radar coverage is concerned, the presently programmed number and location of the Canadian fixed radar sites give almost adequate coverage north of our eastern target complexes. It would be desirable to add a few more radar sites to give greater protection to United States targets in the Great Lakes region as well as to increase the protection of Canadian targets. Within the ZI itself, the fixed sites programmed are somewhat inadequate in some regions but this can be made up in large measure by suitable deployment of the mobile radars.

Data-handling facilities in the planned ground-radar network are inadequate in two ways: First, the ability to handle unknown tracks (in order to make identification and evaluation) is inadequate in some regions with present plotter-teller teams and plotting-board techniques. Secondly, the control capacity, or ability to control interceptors in combat with enemy bombers, is marginally adequate in some regions and inadequate in others. Improvements in data handling can be made in the next few years by the installation of several fairly simple optical and electronic or mechanical devices. One of the most promising equipments is the single-color target-position indicator (TPI). At some additional cost, it would be possible to obtain more effective systems employing multicolor presentation on successive oscilloscope scans.

Further improvements in the control capacity of the radar network in the next few years might be made by having realistic training exercises in which large numbers of bombers and interceptors are involved, by improvising procedures, by the training of personnel, and so on. In the near future, air defense exercises should be conducted which involve large-scale bomber raids and large numbers of interceptors, roughly equivalent to the raid density which is esti-

mated for a Soviet attack several years from now. In addition, attempts should be made to obtain some "loose-control" or "broadcast-control" capability with our interceptors.

The next improvement in the data-handling capacity of the radar network will probably take place when somewhat more automatic, more complex equipment reaches field use. In particular, there are presently four "analog" programs, each promising to develop equipment between now and 1956, which will be directly applicable to the air defense of the ZI. These are the USAF adaptation of the British Comprehensive Display System, the Air Force Ground Reporting System (including the Semiautomatic GCI program), the Signal Corps Project 414-A, and the University of Michigan program for the development of ground-radar control equipment for the Bomarc test vehicle (and for a study of the ground-radar environment for the next generation of interceptors and Bomarc missiles). It has been concluded that the objective of these developments is desirable; however, there appears to be some danger of duplication, and among these projects the tie-in between the radar network, interceptors, local-defense weapons, and ground observers must be worked out. Additional effort should be exerted to see that at least the three Air Force programs are closely co-ordinated with the needs of the Bomarc missile development and the MX-1179 interceptor-electronics program. A statement of the requirements for each of the components of these projects and a preliminary time schedule should be worked out in detail by joint action of the interested parties.

A somewhat different program for improving the data-handling and control capabilities of the radar network is being pursued by Project Lincoln at Massachusetts Institute of Technology. This system employs narrow-band transmission of the radar data to centrally located digital computers. The program appears promising and should be encouraged.

Both this digital program and the analog programs should continue until enough equipment has been produced to permit operational trials. However, it is important to see that the programs go in such a direction as to permit an orderly growth from the present radar system and the low-altitude augmentations of Sec. III.

II. Inadequate Identification Procedures and Rules of Engagement

Present identification procedures rely largely on flight-plan matching; if possible, interceptors are dispatched to investigate those aircraft not meeting

flight-plan tolerances. For flights entering the country, these procedures are inadequate for several reasons: A large percentage of friendly aircraft fail to meet their flight plans. At the present time many of these intrusions cannot be investigated with interceptors because of our limited all-weather interceptor capability and limited radar cover. Even if interceptors contact the unknown aircraft, visual recognition may not be satisfactory at night, in bad weather, or if the aircraft is a B-29, which is similar in appearance to the Soviet TU-4. For flights within the country, the situation is even worse, because the large number of flight plans and aircraft tracks which have to be handled overloads the identification capabilities of the GCI stations. Because of the inability of our present identification system to give identification in which air defense commanders can have confidence, the present rules of engagement are that an aircraft can only be fired on if:

1. It is manifestly hostile in intent.
2. It commits an overt hostile act.
3. It carries USSR markings and appears without prior arrangements.

Obviously these rules do not depend on previous identification procedures. It only takes a can of paint to nullify rule (3) and action taken by rule (2) is probably too late. By the time that the interceptor decides that the aircraft is manifestly hostile in intent it may also be too late to take effective action by rule (1).

Some steps which would improve our identification capabilities are enumerated below:

1. Complete the permanent-plan radar network and add picket-ship and AEW cover as specified above. Complete the program for all-weather interceptors and recovery facilities.
2. Perform the basic identification in a belt outside the boundaries of the ZI and have such tight control over internal traffic that in the event of hostilities friendly aircraft can be grounded or diverted from critical areas on short notice.
3. Apply the following principles to identification of entering traffic:
   a. All overseas aircraft should be required to land outside the ZI and be inspected and briefed as to entering procedures. This outside landing point should be near the ZI if possible and it would be very desirable for it to be within radar coverage from the ZI, although this will not be possible in many cases. In some cases,

unfortunately, the outside landing point may have to be the overseas takeoff point.

b. The points of entry of the identification perimeter must be within solid radar coverage.

c. The points of entry must be well outside critical target areas, i.e., at distances sufficient to permit interception if something goes wrong. This distance should be at least 200 miles.

d. The penetration point must be marked by a beacon or omni-range system.

e. The traffic should be so tightly controlled that the load can be adjusted to be smoothly spaced to prevent several aircraft from coming in close together.

f. An authentication procedure—the code being given to the pilot at the briefing point—must be worked out which gives a virtual certainty of correct, rapid identification of all flights as hostile or friendly.

g. A fail-safe feature should be added so that unless the pilot of an aircraft is notified that he is friendly he must direct his flight to an alternative check point to be inspected before proceeding.

It is felt that the authentication desired cannot be accomplished solely by the use of such electronic devices as the Mark X IFF system but must be achieved by several operational procedures. To work out the most effective and practical procedures requires detailed knowledge of CAA and airlines problems, air defense radar and interceptor properties, characteristics and availability of navigational aids, etc., and it is suggested that a working group be called together to adopt a new program of identification procedures and rules of engagement.

III. Inadequate Defense against Low-Altitude Attack

The possibility of a very-low-altitude attack by enemy bombers has been investigated, and it appears that such an attack is feasible for the delivery of atomic weapons on our targets. This seems, in many ways, to be a very attractive form of attack for the Soviet Union to employ. A deficiency exists in the defense against this low-altitude attack because of:

- The lack of radar coverage for control of interceptors.
- The ineffectiveness of interceptor AI radar at extremely low altitudes.

- Reduced effectiveness of interceptor armament at very low altitudes as a result of restricted tactics.
- The very low effectiveness of present light guns as low-altitude defense weapons, particularly if the enemy bombers use formation attacks or deliver their payload by means of glide-bomb techniques. In any event, the number of such light guns or automatic weapons presently planned for the defense of this country is inadequate to achieve a noticeable defense.
- The limited low-altitude capability of the 90- and 120-mm guns. It is estimated that because of their low rate of fire, high cost, and low slewing rates, they are much less effective against low-altitude attacks, on a cost basis, than the Skysweeper. Because of the greater number of these heavy guns presently programmed, they will make a definite increase in the low-altitude defense strength but not enough to meet the low-altitude problem adequately.

The defense against a low-altitude attack was found to present the most difficult problems considered in the Air Defense Study. The likelihood and probability of success of such an attack hinges on the ability of the enemy in navigation, target recognition, and bomb delivery at such altitudes. Although these abilities are considered to be adequate in the present study, there is need for tests to determine the operational limitations of low-altitude attack and bomb delivery. Such tests would have a two-fold purpose: to assist in evaluating the effectiveness of defense weapons against likely low-altitude threats and to determine what capability exists or can be developed for carrying out low-altitude strategic bombing attacks against the USSR.

Detailed consideration was given to the steps which must be taken to obtain low-altitude data-network coverage and low-altitude weapon performance. These are discussed below.

LOW-ALTITUDE DATA-NETWORK COVERAGE

Low-altitude coverage over land is presently intended to be furnished by the Ground Observer Corps (GOC). As now constituted, this Corps is completely incapable of furnishing accurate data rapidly enough for close control of interceptors. It has been concluded that in order to make the GOC effective, it will be necessary to increase public interest greatly and to enlist many more people in the program; to increase the speed with which data are transmitted from the

ground-observer posts to the filter center or to other central data-storage points by having hot telephone lines at all times; and probably to add several small electromechanical devices or to make procedural changes to get effective performance from this Corps.

There appear to be two general ways in which interceptors can be controlled by the GOC. First is the so-called "Terrier" technique, advocated by the British. By this method, operational control of interceptors is turned over to the ground-observer personnel at the filter center and they communicate by their own radio channels directly with the interceptors. Operational trials of this technique would help to evaluate its importance in air defense. A second technique would transmit the data from the ground-observer posts directly to the GCI with such accuracy and speed that they could be used for control purposes by the radar controllers.[5] This kind of operation of the GOC requires much more extensive application of equipment and facilities and involves a development program. The problems involved are analogous to those which must be met in attempting to tie in low-altitude radars with the present high-altitude network.

Low-altitude coverage over land may also be achieved by closely spaced ground radars. The problems associated with this solution to the low-altitude-coverage problem are first, the economics of any such extensive network of radars, and secondly, the technical problem of transmitting data from these radars to central places and then assimilating the data for identification, evaluation, and control purposes. To provide this low-altitude radar coverage, several possible methods have been studied which are applicable to various time periods. In the first period, from 1953 to 1955, a quick-fix solution is sought. It has been concluded that there is a definite possibility of getting low-altitude radar coverage over land during this period. Broadly speaking, this could be done as follows: The radar gathering heads would be, for example, radars of the type used for airport surveillance; these radars are quite well engineered, are reliable, and can be operated with minimum manning. Elimination of ground-clutter signals would be by means of the mercury delay line presently incorporated with these radars. They could be mounted on 60-ft towers for good low-altitude coverage. Several schemes described in Chap. 12 achieve narrow-band transmission, permitting the target data to be put on telephone lines and transmitted to the nearest GCI radar. At this point, the data would be incorporated, probably into the target-position indicator (TPI), so that low-

[5] Filter centers might still be required to suppress duplicate tracks, but it is hoped that such centers could be eliminated completely.

altitude target information could be projected with the high-altitude information on the vertical plotting board. In addition, the low-altitude data would be fed directly into the video of the large radar, perhaps by improved video-mapping techniques or by Iconoscope techniques, so that the low-altitude data would be available at the directors' consoles, and low-altitude interceptions would be controlled in the way that high-altitude interceptions are now controlled. This solution appears both feasible and important in improving our low-altitude air defense capability.

The GOC could use somewhat similar techniques to aid in the rapid transmission of data to the GCI centers. It has been concluded that it is possible to develop data-handling methods which will permit ground-observer data to be introduced into the GCI center with sufficient accuracy and rapidity to permit the control of interceptors from these data. Such an improved GOC would complement the low-altitude radar coverage described above, being more attractive in heavily populated areas and in areas where there is large normal peacetime traffic, for example. It is proposed that ground observers send coded position data (plus some data on aircraft identity, sizes, and number) directly to telephone exchanges, either on hot lines or on phantom circuits. Mechanization at the GOC post might be possible, but since there is some indication that the nature of the telephone plant in rural areas would make this difficult, the mechanization should possibly begin at the local exchange instead. At the exchange, a storage device would be employed so that the data could be fed at an optimum rate over a telephone line directly to the GCI. This or similar methods of storage would be used for the data from all exchanges reporting into the GCI center. The data could then be taken out of storage at a fast rate and placed on a plan-position-indicator (PPI) scope so that they could be employed in the same way as primary radar data.

In the period starting about 1955, the data handling in the GCI center itself may be supplemented by development growing out of the Air Force Ground Reporting System, the University of Michigan program, the Signal Corps Project 414-A, etc. In prosecuting these projects emphasis should be placed on making certain that they are compatible with those forms of low-altitude data gathering which show promise of being operationally available at the same time.

When somewhat later time periods are considered, it is recognized that the small radars with mercury-delay-line moving-target-indicator (MTI) kits are not the ultimate in low-altitude gathering heads. A study has been made of the preferred characteristics for a new design of radar for this application. This

radar, called Muldar, is described in Chap. 12. It has been concluded that the most promising line of development to achieve completely adequate rejection of unwanted targets and clutter is to use pulse-doppler techniques, multiple range gates, velocity filtering, and highly stable transmitting and receiving equipment. The transmitters would use crystal-controlled oscillators and high-power-pulsed amplifiers such as Klystrons.

The analysis showed that low-altitude coverage over the oceans is also of primary importance for defense against low-altitude attacks on seacoast targets. The preferred way to obtain this coverage is with AEW aircraft. This merely strengthens the conclusion regarding the PO-2W (C-121C) aircraft in Sec. I (page 12).

PERFORMANCE OF DEFENSE WEAPONS AT LOW ALTITUDE

Interceptors

The present Air Force program calls for the procurement of all-weather interceptors using AI radar whose only special provisions for work at low altitude are velocity-aided tracking to help in the AI gun-laying phase, and sensitivity-time-control circuits, etc., to aid in search. In AI search these radars can be confused by the ground-clutter signals at low altitude. For the next few years it is likely that no major changes can be made in the AI search equipment itself to improve this low-altitude capability. However, something can be done to develop techniques and to train pilots in the use of present equipment. At the present time, the capabilities and limitations of this AI gear at low altitude have not been completely explored. Operational suitability tests of the F-86D, F-94C, and F-89D being performed by Air Proving Ground should be planned to permit the evaluation of the low-altitude limitations of the AI search-and-track gear over various kinds of terrain and over water.

In about 3 years it should be possible to modify the AI radar equipment itself to improve its low-altitude capabilities. Some attention was given in the present study to the question of how to modify the AI radar, but no firm conclusions were reached. Part of the effort of the MX-1179 program is directed toward improving this capability. Since the achievement of a low-altitude capability in the AI radar, in the air-to-air missile seeker, and in the Bomarc missile seeker presents problems of a similar nature, a fundamental research effort should be made to explore promising techniques for obtaining this capability.

In addition to the AI radar itself, there are also, in search-and-track phases, many low-altitude limitations inherent in interceptor armaments. For the next

few years our interceptors will be armed with 2.75-in. rockets. These rockets are unguided and have no particular low-altitude limitations except that the interceptor must come very close to the bomber before firing. Tactical limitations and the threat of crashing into the ground exist when the interceptor tries to attack bombers at low altitude. For these reasons, in this kind of duel the interceptor is forced into a stern chase, where his probability of killing the bomber is considerably reduced, where the penetration distance of the bomber before the interceptor can fire is increased, and where the interceptor is more likely to be killed by the bomber's defensive armament.

With missile armaments which can be fired at longer range, the interceptor's tactical limitations at low altitude tend to be reduced. The low-altitude problem for these missiles concerns the ability of the missile seeker to discriminate between the desired target and ground-clutter signals. In view of the comparable high-altitude effectiveness of the interceptor armaments considered in this study, and of the importance of low-altitude attack, it was concluded that it is a step backward to replace rocket armament (with reduced low-altitude capability) with missile armament if it has *no* low-altitude capability. The various missile programs are attempting to achieve low-altitude capability. The MX-904 program considers a tactical way to achieve this, whereas the Sparrow program is developing several different kinds of seekers having promise of low-altitude capability. The design of the MX-1554 interceptor should be kept flexible enough to carry MX-904 missiles and 2.75-in. rockets, as presently planned; in addition, the design should not exclude the possibility of carrying Sparrow missiles or large rockets as alternative armaments, at least until the low-altitude capabilities of these weapons are demonstrated or evaluated.

Area-Defense Missiles

At the present time, the development program for the Bomarc I missile includes an attempt to develop pulse-doppler features in the seeker to obtain some low-altitude capability. This phase of the program holds considerable promise.

Local Defense—Unguided Weapons

Several unguided local-defense weapons were studied, such as Skysweeper, 40-mm guns, short-range barrage rockets, etc. These weapons are specifically designed to have low-altitude capability.[6] It is felt that they could be effective

[6] The 90- and 120-mm guns were also investigated and found to be relatively ineffective against very-low-altitude attacks on the basis of cost for a given attrition inflicted on an attacking bomber force.

down to the lowest altitudes considered if they were properly sited (with flak towers in some cases) and if they were properly alerted by low-altitude radar networks or by forward observers, who might also have to be in towers to observe a force coming in at very low altitudes. The difficulty with these weapons is not that their performance at low altitude is inferior to that at other altitudes, but that their low-altitude performance is relatively ineffective for the amount of effort going into these programs. In the absence of low-altitude capability on the part of the high-altitude weapons, such as interceptors and guided missiles, the burden of low-altitude defense must fall on these guns and rockets.

In the early period (until 1954) local defenses in the United States can be strengthened by buying a larger proportion of specifically low-altitude weapons. Against a low-altitude night attack, the Skysweeper gun or Loki rockets appear to be all that are available. Of these weapons, the Skysweeper appeared better in the present study, and it was concluded that if this weapon appears satisfactory in operational trials, it should be bought in preference to 90- and 120-mm guns. Against a very-low-altitude daylight attack, the effectiveness of Skysweeper and Loki was found to be reduced, so that it might be desirable to purchase some 40-mm guns and to mount them on flak towers to combat this threat.

For the later period, perhaps from 1954 on, it is possible to consider the development of improved weapons. Of the weapons examined in the present analysis, the most attractive were the T-131 rocket gun and the "automatic barrage rocket," a novel weapon described briefly on pages 32 and 33.

Local Defense—Guided Missiles

The first local-defense guided missiles suitable for the defense of this country which will appear in operational quantities are the Nike and Terrier I. The Terrier I was designed primarily for naval task force defense. Neither of these weapons, however, is specifically designed to have low-altitude capability at the present time; nevertheless, it is estimated that there could be some low-altitude capability in the Terrier missile, particularly against night attacks, if several changes were made. (See Chap. 9.)

At a somewhat later time, perhaps in 1956 or 1957, it will be possible to have local-defense guided missiles making use of types of guidance systems different from those employed by the Nike or Terrier missiles. The guidance system which has the greatest promise for low-altitude capability is that employing a semi-active homing-all-the-way radar seeker, in which the seeker would employ

pulse-doppler principles. The seeker-receiver in the missile itself would employ both range gates and narrow-band velocity filters, automatically tracking the desired target in range and velocity. In order to make use of the doppler principle, a highly stabilized, high-repetition-rate pulse system would have to be developed. The transmitter on the ground could either be an almost omnidirectional transmitter, illuminating a large portion of the sky around the defended area, or it could be several high-gain tracking illuminators pointed at the desired targets. In any event, in defense against low-flying targets, it would be desirable for the missile seekers to acquire their targets before take-off; the missiles would then be launched vertically and programmed to a nominal altitude; and then the seeker would be allowed to take over and guide the missile in a homing course to its target. In this manner the missile would be approaching the target in such a way as to minimize difficulty with target signals reflected from the ground. In addition, a narrow-band velocity filter tracking the target would minimize ground-clutter signals and permit operation very close to the ground. Although this appears to be the most desirable missile guidance system for a local-defense missile, having both high- and low-altitude capability, no intensive work appears to be in progress toward the development of such a guidance system.

This weapon, possessing both the promise of extremely high bomber-attrition rates inherent in advanced guided missiles and the capability for low-altitude defense, is one of the most promising weapons investigated in the Air Defense Study. The detailed characteristics of the missile seeker and the ground equipment, as well as the general missile design characteristics, are described in Chaps. 9 and 12. It will be shown later that this type of missile is desirable for other reasons and can be improved to combat advanced types of threats.

The most immediate deficiencies of our air defense system have been enumerated. As time goes on and enemy capabilities increase, both in the number and types of offense weapons which may be employed, other deficiencies will become increasingly important.

IV. Inadequate Total Defense Strength

The damage which could be done to this country in one massive atomic strike is so much greater than was achieved in such attacks with high explosives in World War II that the whole concept of the desired bomber-attrition level of active air defense must be re-examined. By 1953 or 1954 it is estimated that

the Soviet Union may possess upwards of 200 bombs, of which perhaps 100 or more could be launched against this country. In the event of war, the money this country spends on air defense will purchase: first, some warning, so that our civil population can take passive defense measures to avoid injury and death as much as possible; and secondly, an active air defense to increase the gross errors, navigational errors, bombing errors, etc., of the attacking force. Over and above these effects, however, the actual attrition accomplished by our defenses must be much higher than that of World War II in order to be of appreciable importance. For instance, if the enemy attack comes in one massive strike, as it well might, in order to keep the number of bombs delivered on our targets under, say, 50, we would need something like 40 per cent attrition in 1953 (in addition to the operational losses and aborts). This figure would rise to perhaps 70 or 80 per cent attrition in later years when the enemy stockpile becomes larger. These attrition rates are so much higher than those achieved in World War II that drastic measures in defense-weapon development must be taken.

A study was first made of our expected air defense capability during the 1953 period with presently programmed defense weapons. It is estimated that in the event of a mass raid of hundreds of bombers, the attrition that our interceptors could inflict would probably be of the order of 15 per cent, if adequate warning of the attack were received and if the attack came at high altitude. Against low-altitude attack in the 1953 period, the interceptor force would be much less effective for the reasons enumerated above (pages 16 and 17), and the major burden of low-altitude defense would fall on 90- and 120-mm guns, on Skysweeper guns, and on automatic weapons. It is estimated that with the number of these weapons presently programmed for use in 1953, the attrition inflicted on a determined force attacking at low altitude would be very low.

In 1953 the interceptor armament would be the 2.75-in. rocket. Calculations of the effectiveness of this weapon indicated that the F-86D's and F-94C's with 24 rockets are inadequately armed. Their armament load should be increased to at least 48 rockets, if at all possible. In the case of the F-89D, the effectiveness of this interceptor depends greatly on whether it can be designed to discharge its ammunition in two or more firing passes rather than in just one. Operational doctrine should be to use at least two firing passes if bomber formations will permit.

For the period after 1953, and particularly from 1955 on, a wider variety of defense weapons becomes possible. These weapons, against a threat of higher-performance manned bombers, were taken to be:

- *Manned interceptors* of higher performance and armed with rockets, air-to-air missiles, or a remote-controlled turret with twin 30-mm guns.
- *Area-defense guided missiles* of the Bomarc I type.
- *Local-defense guided missiles* of the Nike, Terrier, or Talos type.
- *Low-altitude weapons*, including several new types of guns and rockets.
- *All-altitude local-defense guided missiles*, employing semi-active homing-all-the-way guidance.

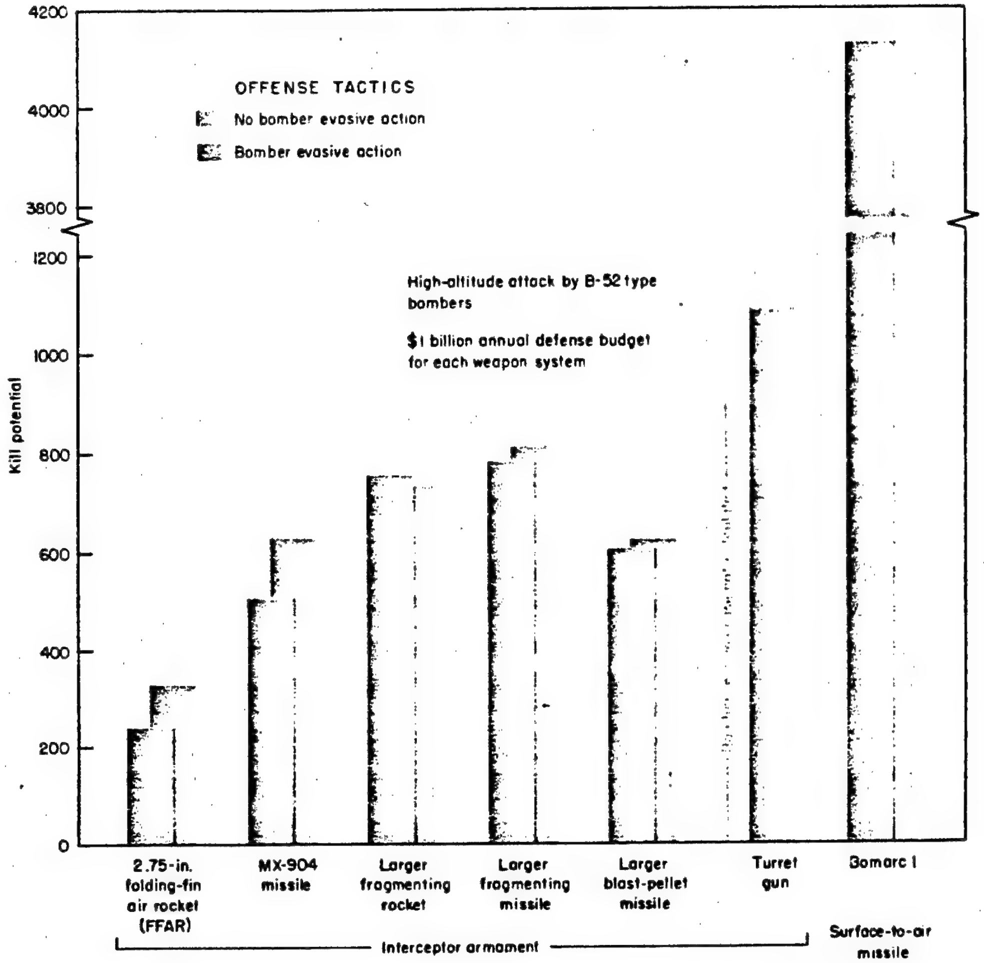
These types of weapons were examined in considerable detail in search of ways to improve our defense strength by an optimum choice of weapon type and detailed weapon characteristics. In making this numerical study, future weapons were considered to work essentially as advertised by their proponents. In the case of guided missiles, reliability factors were used which were felt to be reasonable upper bounds on performance. Thus, these calculations are made to answer the question, If a given weapon works as advertised, do we want it in the air defense picture? These calculations are *not* intended to be a prediction of the performance of such future untried weapons. The results of this part of the study are shown in Figs. 7, 8, and 9 and are summarized below:

MANNED INTERCEPTORS

Manned interceptors with conventional recovery and landing facilities were considered. Interceptor armaments studied included the 2.75-in. FFAR's, MX-904 missiles, a remote-controlled turret mounting twin 30-mm guns, large fragmenting-warhead air-to-air rockets, and large fragmenting-warhead or blast-pellet-warhead air-to-air missiles. A generalized study was made of the interceptors themselves. In each case, the interceptor was chosen to take maximum advantage of the armament type used, and the preferred characteristics of the interceptor and its armament to achieve the maximum kill effectiveness were investigated. The results of the armament comparison are shown in Fig. 7.

On the basis of estimated kills and estimated costs alone, it was found that all armaments considered, with the exception of the 2.75-in. FFAR, gave approximately the same kill effectiveness against high-altitude attack for the same budget in interceptor squadrons.[7]

[7] Note that this is quite different from saying that the armaments were equally effective per missile or rocket. The basic idea of the comparison of this study is that for each armament type the preferred interceptor and armament characteristics were investigated and over-all kill and cost figures were obtained. The armament comparison is on the basis of bombers killed for a certain investment in the interceptor force.



"Kill potential" is an analytical concept designed to facilitate comparisons of defense weapons. In this and subsequent figures, the term is expressed numerically as the maximum number of bombers which would be killed before the bomb-release line if all the defenses of all the targets were brought to bear on an extremely large saturation raid. (In Figs. 8 and 9, the term applies to a single target and is used for the comparison of local-defense weapons.) It includes the effects of weapon availability, aborts, operational degradation, etc., but not the effects of surprise or enemy use of electronic countermeasures.

Fig. 7—Area-defense weapon effectiveness

The 2.75-in. rockets would be roughly one-half as effective in killing enemy bombers as the other armaments considered.

No novel interceptor armament was discovered showing any marked improvement over the MX-904 missile, which is presently part of the USAF program.

The large fragmenting and blast-pellet warheads appear quite promising, but aircraft vulnerability and VT-fuze performance data are at present insufficient to permit really firm estimates to be made. Further work should be instituted on these types of warheads and on improving VT fuzing. Where fragmenting warheads are concerned, more data are needed on the vulnerability of components of modern bombing aircraft, in particular on vulnerable areas of turbojet engines, radar bombing systems, atomic bombs, and fuel.

Explosive pellets appear to have considerable promise, but further data are needed on the effects of altitude and incident velocity on this warhead type.

The preferred warhead size for the large fragmenting missiles is in the range of 75 to 150 lb. This is considerably larger than the present Sparrow or Meteor warheads.

To be most effective, the fragmenting-warhead missiles must burst at a certain distance from the target, this distance depending on the direction of approach of the missile. A simple VT fuze would not detonate the missile at this optimum point for all approach paths. There is need for the development of sharp-angle microwave fuzes with variable pre-set delays or, even better, with delays depending on the approach course to the target. The numerical results presented here are based on the conclusion that the development of a reliable microwave VT fuze with pre-set delay is feasible.

The large fragmenting-warhead rockets appear quite effective, but the lack of firm warhead data prevents any strong conclusion at this time about the desirability of developing this weapon. As better warhead data become available, the question of the development of such a rocket should be reviewed.

The most effective interceptor weapon against a nonevading bomber (see Fig. 7) appears to be the turret gun. This is *not* the turret-gun system presently under development by the USAF. It employs larger guns and higher-power radar and is essentially a new development which could not be expected to reach operational use before 1956. It is felt that this armament is very susceptible to bomber evasive action. Present development difficulties indicate that this armament may not be practical or reliable for supersonic interceptors. For

these reasons the turret gun is not considered a preferred armament in this study.

Note that toss-bombing and ramming interceptors were not included in the present study. It is believed that they would not increase interceptor kill effectiveness markedly over the weapons considered, and the attendant uncertainties and discontinuities in present development and training programs argue against them.

In the design of the interceptor itself, the following characteristics were found to be desirable:

Combat radius: about 150 to 350 nautical miles. In studying preferred combat radius, a large number of factors were taken into account, including the geographic properties of the target system, the cost of increased radius of interceptors, the cost of increased radar coverage, requirements of radar coverage as a function of interceptor combat radius, etc. It is interesting to note that detailed calculations showed that the effectiveness of interceptors is rather insensitive to combat radius over the range mentioned.

Powerplant type: turbojet with afterburner.

Interceptor speed: in combat, about 15 per cent speed advantage over the fastest threat it is expected to meet. A price is paid for increased performance of the interceptor, however. For example, analysis showed that to combat a Mach 1.3 threat, about one and one-half to two times as expensive an interceptor force would be required as was required to combat a Mach 0.9 threat and obtain the same number of bomber kills.

Maneuverability. A transient load factor of about 1.5*g* was found to be adequate for collision-course armaments of this study. Time-to-climb (to a combat altitude of 50,000 ft) of about 7 minutes was found to be acceptable.

Armament load. For most of the armaments studied, the preferred armament load, including the installation and accessories, was about 1500 to 2000 lb. Expressed in terms of numbers of rockets or missiles, calculations showed that the preferred load was of the order of sixty 2.75-in. rockets, twelve MX-904 missiles, or three of the large fragmenting-warhead air-to-air missiles or rockets. In most cases it was found to be advantageous to have the interceptor operate so as

to fire its armament in two or three firing passes rather than in one, if the enemy bomber formation spacing was such as to make this feasible. In the event that only one firing pass is considered to be feasible, the optimum armament load decreases somewhat, so that, in the case of the MX-904 missile, for example, the optimum load appears to be about eight missiles.

The conclusions presented about preferred interceptor combat radius, number of firing passes, time-to-climb, etc., are dependent on the operational environment and design restrictions imposed on the interceptor force. In this study it was assumed that there would be only a single type of interceptor in the force, that conventional take-off and recovery methods would be used, and that the interceptors would defend both seacoast and inland targets and isolated and clustered targets.

A type of interceptor which has not been investigated in this study is one using unconventional take-off and recovery, ramming, and perhaps cheap, short-life components. Such an interceptor would compete with local-defense missiles.

AREA-DEFENSE GUIDED MISSILES

In comparing area-defense missiles, such as Bomarc I, with manned interceptors, the question of the over-all reliability of the guided missile and its ability to operate in various tactical situations was important. If, in the event of a high-altitude attack by manned bombers, the Bomarc missile is not rendered inoperative by enemy use of countermeasures, etc., and if the over-all reliability of the missile itself and its ground guidance equipment is 50 per cent, for example, the study revealed the missile to be approximately eight times[8] as effective as a transonic interceptor armed with MX-904 missiles, in the sense that the same attrition could be inflicted on enemy bombers for about one-eighth the cost[9] in the weapons themselves. This comparison was made entirely on the basis of cost and attrition, neglecting questions of over-all technical feasibility, enemy electronic countermeasures, etc.

[8] There has been a slight downward revision in warhead-effectiveness calculations, and consequently in kill potential, of the Bomarc I since previous presentations of results.

[9] That is, if a sufficiently large number of missiles is produced to achieve low mass-production costs. This is probably something like 10,000 missiles.

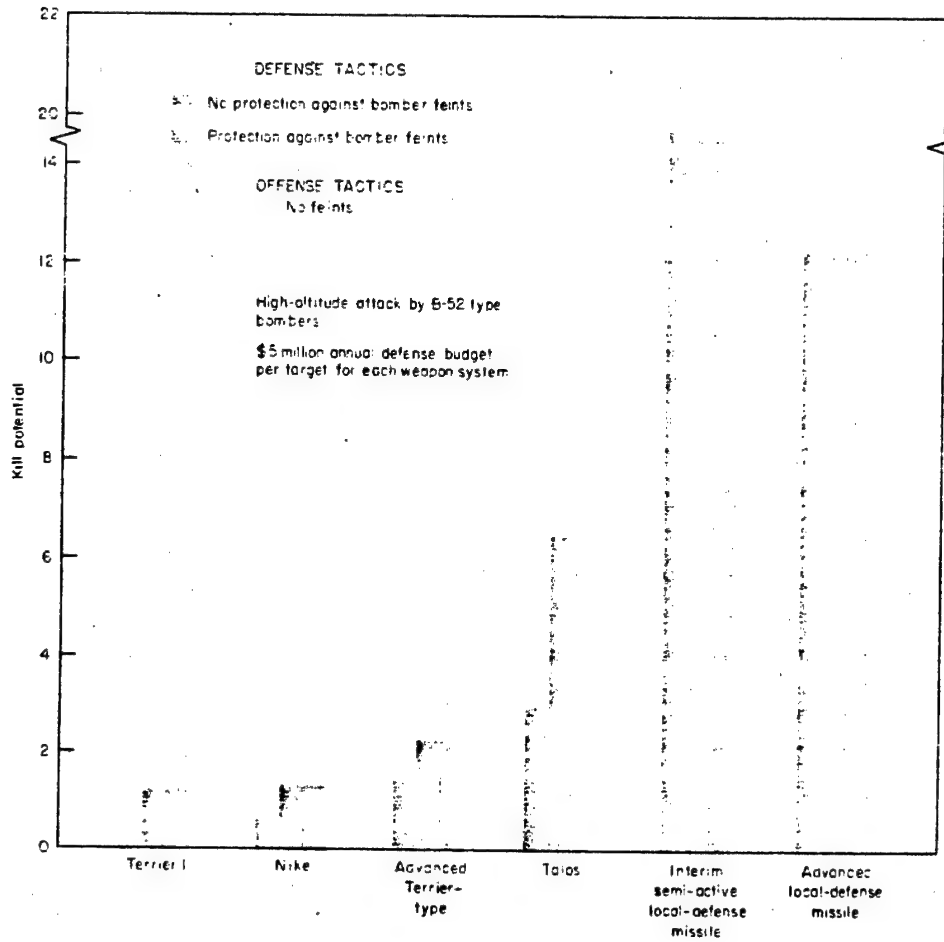


Fig. 8—Local-defense missile effectiveness

LOCAL-DEFENSE GUIDED MISSILES: NIKE, TERRIER, AND TALOS

Against a high-altitude attack, the Nike and Terrier I missiles proved to have essentially the same defense strength for the same budget. This defense capability was roughly comparable with that of the interceptor force composed of F-86D and F-94C interceptors, so that these two kinds of weapons would both find a place in the 1955 period. The advanced Terrier-type missile[10] was somewhat superior to these first two missiles, and the Talos missile seemed to

[10] The characteristics of this missile represent a "best guess" by RAND of the improvement to be expected in the Terrier missile program in the next few years.

be about five times[11] better than the Nike or the Terrier I against subsonic bombers attacking at high altitude. This showed the Talos missile to be roughly comparable with the improved interceptors expected to be operational at the same time as the Talos missile, namely, in the 1957 period. Again the low-altitude capability of these weapons is much reduced, and in some cases it is almost negligible when compared with the high-altitude capability. (See Fig. 8.)

LOW-ALTITUDE GUNS AND ROCKETS

Of the low-altitude guns, rocket guns, and rockets currently under development, the one giving the most defense for a given cost against a daylight attack is the visually fired T-131 rocket gun. The absolute effectiveness of this gun against a low-altitude attack, as compared with the effectiveness of other weapons against a high-altitude attack, depends on enemy bomber formation size, evasive action, use of air-to-surface missiles or glide bombs, etc. Kill potentials of these weapons are shown in Fig. 9.

The most favorable case for the defense was found to be one in which the enemy bombers were assumed to come over singly, with no evasive action and no glide bombs or air-to-surface missiles, in a low-altitude (200-ft) daylight attack. In this case, the absolute effectiveness of the T-131 gun (on the basis of cost for a given defense strength) is noticeably better at its design altitude than the Nike and Terrier I missiles at their high design altitude and is about three to five times better than present 40-mm guns. The Loki and Skysweeper weapons are roughly comparable in effectiveness; both have a nighttime capability and are less than one-half as effective against 1500-ft night attacks as the T-131 is against 200-ft day attacks. The effectiveness of Skysweeper and Loki against extreme low-altitude daylight attacks is considerably reduced.[12]

If a different case is investigated, such as one in which the enemy bombers fly tight cells of up to five bombers, take limited evasive action, and perhaps launch glide bombs or crude air-to-surface missiles of about 10-mile range, the kill capacity of these low-altitude weapons is reduced at least 90 per cent. It is largely because of the possibility that some of these conditions might be

[11] Again this means the same attrition for one-fifth the cost if mass-production unit costs are achieved.

[12] Some of the kill potentials have been revised since previous presentations of the results. In particular, more realistic field degradation factors and a better firing doctrine were used in finding the kill potentials of the Skysweeper and Loki.

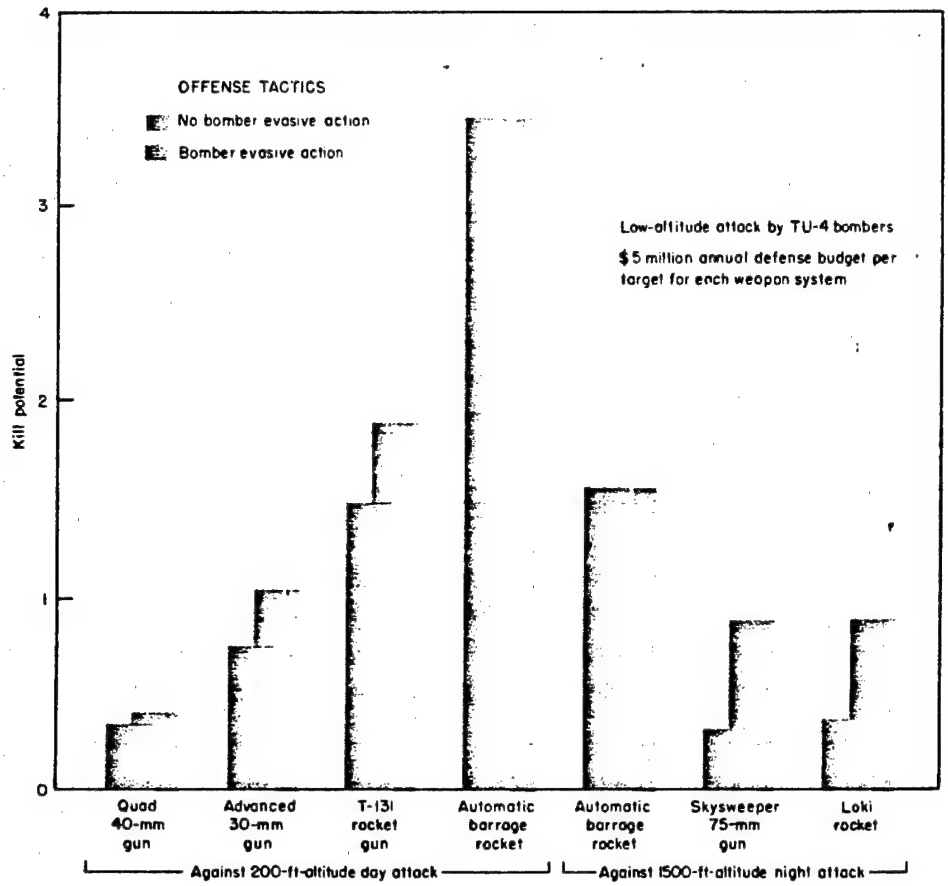


Fig. 9—Local-defense gun and rocket effectiveness

achieved by the enemy that the low-altitude attack is regarded so seriously in the present study.

To get increased defense strength from these low-altitude weapons against a low-altitude night attack, either a way must be found to make the T-131 gun effective without materially increasing its cost or a new weapon must be developed.[13] The T-131 gun might be used at night either with searchlights or flares, or perhaps with infrared trackers. The operational feasibility of these methods was not determined in the present study.

One unconventional weapon type was studied which promised both a day and a night low-altitude capability. This was the "automatic barrage rocket" system

[13] There is also the hope of a low-altitude night capability from the Terrier I missile or the interceptor.

consisting of a ring of cheap unguided rockets emplaced around a target and fired upward automatically when an aircraft penetrates the coverage of modified VT fuzes deployed in a ring just beyond the rockets. The study of this weapon indicated a defense strength somewhat superior to that of the T-131 gun in daylight and also a low-altitude night capability for no extra cost in guidance equipment; however, since the effectiveness of this weapon decreases rapidly with increased bomber altitude, more money must be spent on rockets to get equally strong 1500-ft night defense. This weapon system is so unconventional that it was not possible to decide how practical it would be operationally and logistically. It was concluded, however, that the T-131 rocket gun should be bought and that the automatic barrage rockets are the most attractive low-altitude weapons for further study.

ALL-ALTITUDE LOCAL-DEFENSE GUIDED MISSILES

An interim-period (1957) generalized guided missile,[14] designed to combat manned bombers and making use of semi-active homing-all-the-way guidance, was considered. This missile might employ either one transmitter installation at each local-defense area, with essentially hemispherical coverage, or a set of high-gain tracking illuminators. At budget levels typical of what might be expected for such a weapon as a major element in United States air defense, the all-around illuminators would give much higher weapon effectiveness, since a much larger fraction of the budget could go into the missiles themselves rather than into the ground guidance equipment. In this case, the analysis showed this missile system to be about four times as effective as the Talos missile against a subsonic bomber attack, since about four times as much money would have to be spent on a Talos system to obtain the attrition that could be obtained by this semi-active missile system. This result made the semi-active missile with all-around illuminators the most economical local-defense missile of the present study, and therefore the one giving promise of the greatest defense strength. This defense strength is comparable with that which could be obtained by using the Bomarc area-defense missile under ideal conditions. If, instead, high-gain tracking illuminators were used, the economic advantages of this missile system would tend to disappear and it would become almost as expensive as the advanced Terrier-type missile for the same defense strength.

[14] Such a weapon represents the result of a search for a preferred member of a large family of hypothetical future missiles.

It has been suggested that an interim ground-to-air missile using semi-active homing-all-the-way guidance might be obtained by utilizing ground installations of MX-904 or Sparrow missiles. The present study indicates, however, that short-range, small-warhead missiles of this kind would require a missile defense system so expensive that the economic advantages of the semi-active homing-all-the-way principle mentioned above largely disappear. The missile requirements for an economically attractive system appear to call for a sea-level range of 20 miles and a warhead weight of 500 lb.

* * *

Summarizing the five points discussed so far under "Inadequate Total Defense Strength," it is apparent that against a high-altitude attack the weapons having the most promise, if they are technically feasible and if they are not weakened by enemy countermeasures, resolution of multiple targets, and other such factors, are the Bomarc area-defense missile, the interim semi-active local-defense missile with all-around illuminators, and lastly, the manned interceptor armed with MX-904 missiles, larger missiles with fragmenting or blast-pellet warheads, large rockets, or turret guns.

The greater the defense strength we are able to achieve in this country against high-altitude attack, the greater the probability that the enemy will make a low-altitude attack; therefore it becomes important to determine whether we can achieve a high defense strength against low-altitude attacks in this time period. None of the weapons specifically considered for low-altitude use in this study promised a defense strength comparable with that indicated for the Bomarc area-defense missile or for the semi-active local-defense missile. It is for this reason that the achievement of low-altitude capability in one or more of these advanced weapons is considered so important. The semi-active local-defense missile using pulse-doppler techniques has promise of achieving a low-altitude capability and is thus considered to be an extremely important weapon. There is also promise of a low-altitude capability on the part of the Bomarc missile, but this is considered to be a technically difficult problem. In the same manner, there is promise of a low-altitude interceptor capability, particularly if unguided weapons are used for interceptor armament or if missile seekers are developed with discrimination against ground clutter.

* * *

The next question investigated was: Do even these advanced types of weapons, with their promise of great defense strength, give us enough protection for reasonable budget levels to permit us to survive an atomic attack?

Figure 10 shows the results of calculations of the damage which might be done to this country in one massive atomic strike by the Soviet Union. This illustration is felt to be applicable to our air defense at some distant date. perhaps 1957. Some of the conditions for this calculation were:

- High-altitude night attack with radar bombing.
- Attack directed against industrial targets.
- Three hundred atomic bombs assigned to this attack.
- A high subsonic turbojet bomber. similar to our B-52.

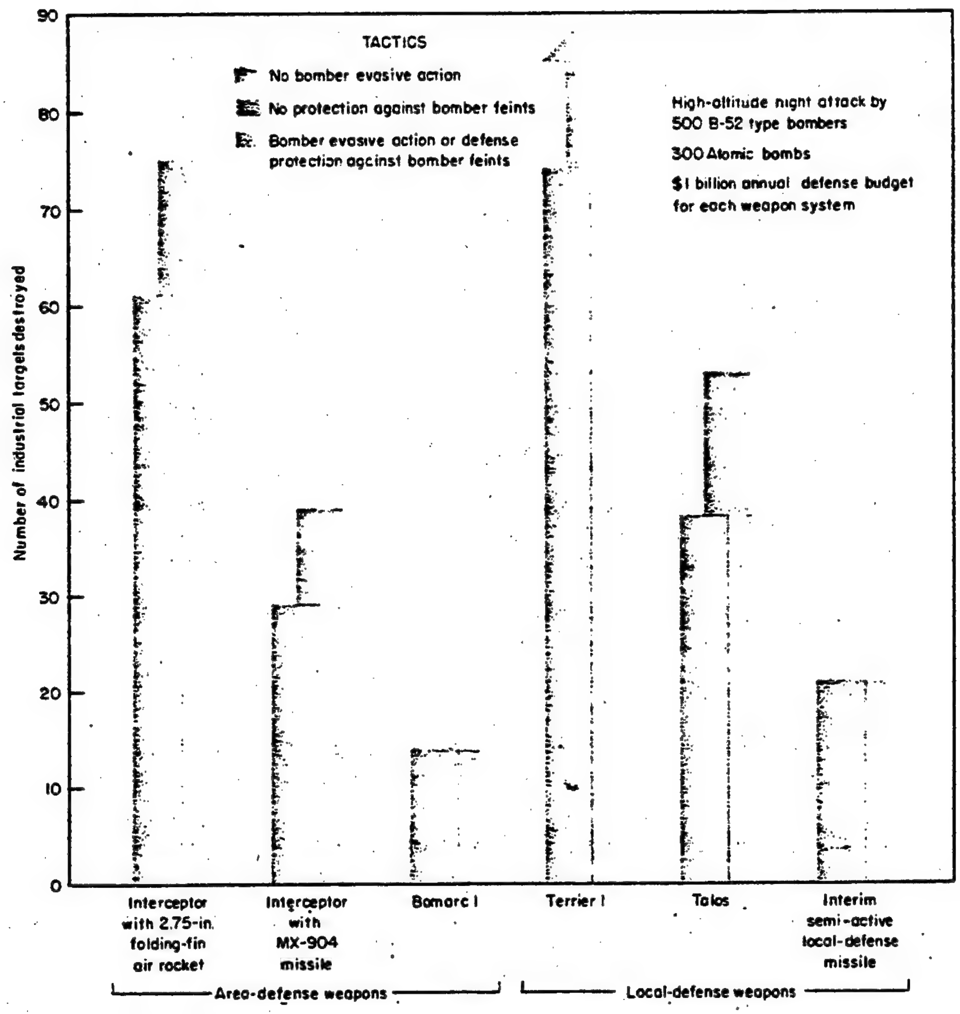


Fig. 10—United States industrial targets destroyed (500 bombers in enemy stockpile)

- Defense weapon budget of $1 billion per year for the particular weapons shown. This does not include the cost of radar networks, other defense weapons, etc., but does include organizational and training overhead costs.
- Over-all missile reliability, including both the missile itself and its ground equipment, taken to be 50 per cent.
- No consideration of the effect of enemy countermeasures, failure of our defense because of being caught by surprise, etc.

This calculation can be considered to be an upper bound on the attrition which we could hope to inflict on an enemy force if everything went well, since the last two conditions are equivalent to saying that our defense weapons will work as advertised.

A similar calculation for a smaller number of attacking bombers is shown in Fig. 11. The conditions are the same as those just enumerated, except that 150 bombers and 150 bombs are committed to the attack on United States targets. These numbers are typical of the smallest raids that could have a decisive effect.

The general conclusions drawn from Figs. 10 and 11 are:

- Local-defense weapons and area-defense weapons have roughly equivalent effectiveness against high-altitude attack at each period in the future *after* the advent of the first local-defense guided missiles.
- Even under the ideal assumptions of these calculations, Terrier missiles or interceptors armed with 2.75-in. rockets are not effective enough to prevent serious damage to our target system in the event of a determined, well-executed enemy raid.
- Improvement is made when the Talos-type local-defense missile or missile-armed interceptors are used for defense.
- The weapons which appear to hold most promise of preserving almost all of our targets and providing an annihilation defense against a determined mass raid were the Bomarc area-defense missile and the semi-active homing-all-the-way local-defense missile with all-around illuminators. With these weapons, the problem is to achieve reliability, tactical flexibility, low-altitude performance, invulnerability to enemy countermeasures, etc. Their basic design is about as efficient in terms of bomber kills for a given cost as it is possible to get without some completely radical change in techniques.

Although in Figs. 10 and 11 the missile-armed interceptor appears to protect fewer targets, it should be remembered that it is probably a more flexible weapon and may come closer to achieving predicted performance in actual combat. In addition, if the enemy lays on several strikes, the recoverable interceptor is further favored. In the present study the interceptor is thus considered an important defense weapon and recommendations are made about steps to be taken to improve its effectiveness. However, the Bomarc I and semi-active missiles are considered to be extremely important weapon-development programs.

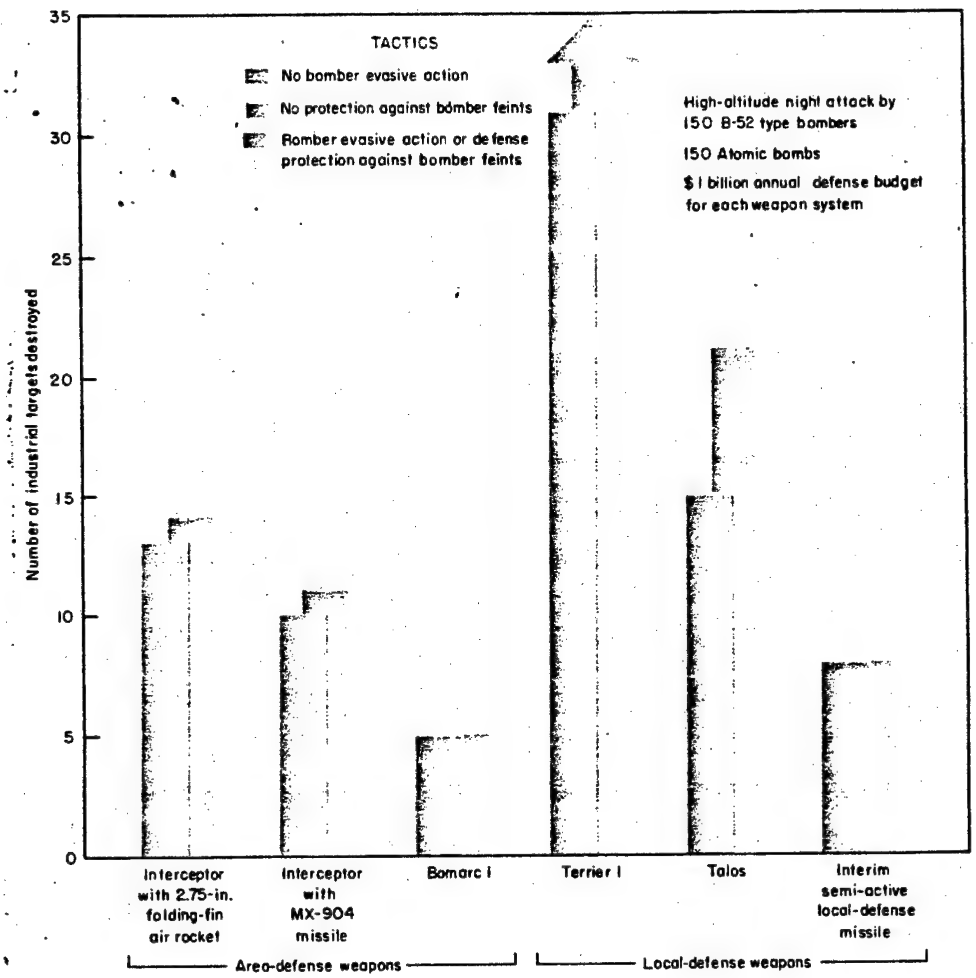


Fig. 11—United States industrial targets destroyed (150 bombers in enemy stockpile)

It is obviously an oversimplification to consider defense by pure systems of single weapons, as shown in Figs. 10 and 11. In practice, there are targets and target complexes suited to defense by local-defense missiles, and other places where, for example, an area-defense missile would be preferred; consequently, in actual practice one would expect to have a mixture of these weapons. Local defenses would be favored for the defense of seacoast targets, isolated targets, and extremely valuable targets.

In order to increase our defense to the maximum possible strength, other things than the choice of preferred weapon types and weapon characteristics must be considered: for example, the question of the proper deployment of our defense weapons.

Most of the present study assumed that the defense weapons would be deployed at or near the target concentrations to be defended. However, consideration was given to the deployment of these weapons in peripheral belts around the edges of the defended area and to the deployment of defenses in forward areas much closer to the enemy take-off bases. In particular, the concept of basing interceptors in Alaska, the extreme north of Canada, Greenland, Iceland, Scotland, etc., to combat enemy bombers near their take-off points was examined.

There are serious technical difficulties associated with any such scheme: problems of obtaining early-warning and control data from radar stations in such outlying areas and of maintaining interceptor squadrons under such logistically difficult conditions. Neglecting these considerations, however, and examining the expected bomber kills and defense-weapon budget expenditure, the analysis showed that when many kinds of enemy tactics were considered, this arrangement of defense weapons was not as effective as deployment in the ZI near the critical areas to be defended. Furthermore, it was concluded that any such forward deployment of weapons would involve a calculated risk, gambling that the weapons would be located in the path of a large fraction of the enemy force. Therefore, such tactics cannot be looked upon with any degree of confidence as being likely to increase our air defense capability materially. On the other hand, a forward extension of some of our radar coverage has many attractive features. A very definite conclusion of the present study is that the radar coverage should extend far enough away from the boundaries of the ZI to reach areas of minimum normal air traffic, so that the presence of hostile bombers, even in small numbers, will be much more noticeable than if the radar coverage is limited to the ZI itself or very close thereto. Thus, it was concluded that the minimum outward extension of

our radar coverage over our oceans and into Canada should be of the order of 400 miles and should use AEW patrol aircraft and picket ships over the ocean. This scheme could be extended by use of AEW patrols farther out to sea, giving even more early warning and helping to minimize the chance of being caught by surprise.

Another question which was examined was the effect of electronic countermeasures on our air defense capability. Both our use of electronic countermeasures against the enemy and the enemy's use against our defense weapons were considered. Equipment characteristics were estimated for the time period of the present study and tactical studies were made of the effect of vigorous employment of these electronic countermeasures. The conclusions were as follows:

- Electronic jamming of the enemy's bombing radar or navigational radar did not appear very promising because of the expense, the uncertainty in our knowledge of enemy bombing techniques, and the difficulty in accurately tracking the bombers by passive means if they fly close together, with their radars on the same frequency. There is also the chance that they might use anti-jamming devices (which we are already developing in this country) and the chance that they might drop their bombs effectively even when the bombing radar is jammed. It was concluded, however, that development work should be continued on this type of jamming equipment, but that its primary application will probably be in local defense against bombing radars at important point targets.

  Electronic jamming of enemy navigational radar or of air-to-air communications was not considered worth while.

- Passive detection measures associated with the ground radar network were also considered to be somewhat undependable, but since they could be inexpensive, it was concluded that they are worth while in fringe areas for pre-early-warning and for additional identification, especially during the next few years.

- The vulnerability of our ground radars to enemy use of noise jammers, chaff, etc., was studied, and it was concluded that within a few years steps should be taken to reduce the vulnerability of these radars. Simple things which could be done are to train operators to read through chaff and to develop operating procedures for switching to various combinations of the radar beams and for tilting the beams.

Somewhat more extensive changes would involve an increase in transmitter powers, spreading the transmitter frequencies over a broader band, and the use of several antenna polarizations. Finally, something should be done about decoying homing missiles away from the radar antenna.

- Ground-to-air communications systems can be made less vulnerable by making certain that transmitter powers are at least 1 kw, that channel redundancy is exploited as much as possible, and that some antenna gain is furnished for the ground transmitters.

If these steps are taken, it is estimated that our air defense system should be tolerably invulnerable to the enemy use of electronic countermeasures for the next few years. As more advanced equipments, including various types of missiles, become available, new countermeasure problems will arise. Therefore, it is important to reflect the best current knowledge on countermeasures in these developments.

V. Inadequate Defense-Weapon Performance against Advanced Threats

It seems reasonable to assume that the enemy capability, as the years go by, will include higher and higher performance offense threats, ranging from high-subsonic-speed bombers to low-supersonic-speed bombers, into the field of supersonic air-to-surface missiles, and ultimately reaching high-supersonic surface-to-surface missiles. It is, of course, extremely difficult to predict the time at which the enemy will solve the difficult long-range guidance and other technical feasibility problems to make such high-performance systems a serious threat to this country. However, it is recognized that consideration must be given to the development of our defense weapons in the direction of higher and higher performance to meet this possibility.

The highest-performance threat considered specifically in the present study was a Mach 3 air-to-surface missile having a range of several hundred miles and a maximum altitude of 100,000 ft. This offensive-missile performance represented the line of demarcation between these air-to-surface missiles and really high-performance long-range glide rockets and ballistic rockets. These latter threats are at so much higher speeds that quite new defense-weapon problems are posed. No detailed conclusions were reached in the present study about

preferred defenses against these very advanced threats, but it appears that the preferred defense may well be a further outgrowth of the semi-active homing-all-the-way local-defense missile discussed above. Studies of these problems are continuing.

A preferred area-defense missile and local-defense missile to combat the 100,000-ft Mach 3 missile threat were studied in a generalized way with the following results:

ADVANCED GENERALIZED AREA-DEFENSE MISSILE

It was concluded that the desired area-defense missile to combat this threat would have to have the following characteristics:

- A warhead designed to achieve fast kills against either missiles or manned bombers. Present estimates are that this could best be realized by using fragments against missiles and external blast or blast pellets against the bombers. It is economically advantageous to make the warhead large enough to secure a very high single-shot kill probability. If satisfactory terminal guidance were achieved and miss-distances of, for example, 20 ft were realized, the preferred warhead would weigh in the neighborhood of 700 lb, and kill probabilities of 0.9 could be expected.
- A capability of a maneuvering load factor of 5*g* at an altitude of 100,000 ft and up to 15*g* at lower altitudes. This maneuverability has been found to be necessary to give adequate all-altitude protection against an advanced type of enemy-missile threat.
- Improved radar seeker performance to achieve a reasonably high probability of successful homing. For seeker antenna sizes of about 2 ft, for example, an average transmitter power of about 500 watts and field maintenance of equipment good enough to preserve almost laboratory performance are required.
- A range of several hundred miles.

To make this missile feasible, radome material able to withstand very high temperatures will have to be developed.

Very critical to the operational usefulness of the missile is the application of design features and maintenance procedures which allow the missile to be continually maintained in a ready-to-go condition. Both of these requirements also exist for the local-defense missile discussed below.

For the advanced area-defense missile to become really effective, development work must be done on warheads capable of inflicting fast kills on manned aircraft and on offensive missiles. To accomplish this, research is necessary on the vulnerability of offensive missiles to fragments (in addition to the items mentioned under air-to-air missile research). Tests should be conducted which will provide data on the vulnerable areas of the payload and on the guidance-and-control system of such missiles. Since fragments may strike missiles at very high velocities, studies of penetration, ricochet, and fragment shatter should be made in the unexplored 10,000- to 20,000-ft/sec velocity range. Investigation showed that the major problems connected with such a defense missile have to do with the maneuverability limitations, seeker range limitations, seeker dead-time during target acquisition and lock-on, mid-course vectoring errors, etc., and with the determining of whether successful airborne detection and terminal homing can be achieved against such a threat. The present study indicated that it might barely be within the capabilities of the missile itself and the electronic components to achieve this performance but that the extraction of the utmost in both missile and electronic seeker performance would be equired, as well as a high order of vectoring accuracy from the ground radars.

ADVANCED GENERALIZED LOCAL-DEFENSE MISSILE

Local-defense missiles were studied with a view to obtaining a defense against this same Mach 3 air-to-surface missile threat, and it was again concluded that the most promising guidance system is the semi-active homing-all-the-way type previously discussed. The power required by an all-around illuminator to illuminate successfully such small radar targets as high-speed missiles was very great and is estimated to be very near the limits of the state of the art for this type of radar power.

The missile itself is required to have a sea-level range of about 30 miles to cope with high- and low-altitude targets as well as with the tricky employment of them. Because of the high speed demanded of the missile, a high-temperature radome must be developed similar to the one required for area-defense missiles. Again, as in the area-defense-missile case, development is required which allows the missile to be continually maintained in a ready-to-go condition. There is also a requirement for a rocket capable of a thrust program in two steps. This missile, estimated to weigh about 5 tons, is concluded to be the required second phase of a two-phase missile development program having as its first phase the interim local-defense missile already discussed.

ADVANCED RADARS

The next question was: Can radar-detection and control data be obtained for such advanced threats? Several types of radar have been developed or suggested. They include:

- The AN/FPS-7: an Air Force version of the Navy AN/SPS-2 radar.
- All-altitude Muldar: short-range sets covering both low altitudes and up to 100,000 ft.
- Modifications of the Air Force step-scan radar development.
- The low-frequency fence radar developed by the Air Force.

The analysis did not reach any conclusions concerning a preferred type of radar set for this application. It was concluded, however, that within the next year or so a study of this problem should be made and a preferred line of development recommended. It seems that the requirements imposed on these radars by the use of local-defense missiles are somewhat less stringent than would be imposed if long-range area-defense missiles were used.

VI. General Summary

It is realized that many of the conclusions of the present report are by no means novel and are, in fact, similar to those reached by other agencies studying the air defense problem. Such conclusions have been incorporated in the present report because they were arrived at independently and represent documentation and corroboration of these other investigations. There are, however, several conclusions and suggestions which it is believed will contribute significantly to the solution of the air defense problem. These are:

1. The conclusion that it is technically possible to incorporate low-altitude radar coverage over land in the present high-altitude ground-based radar network within the next few years before digital computer techniques can be exploited.[15]
2. The suggestion that a semi-active homing-all-the-way local-defense missile with pulse-doppler guidance principles be developed.
3. The conclusion that the best presently foreseen form of ground radar to supply low-altitude coverage and to eliminate ground clutter should

[15] Technical discussion and justification of this and the following two points are presented in Chap. 12.

make use of pulse-doppler techniques, multiple range gates, and narrow-band velocity filters.

4. The conclusion that it is technically feasible to obtain both area- and local-defense missiles having a capability against a Mach 3 missile threat if present missile programs consider these advanced types of enemy threats in their choice of characteristics for the interim-period missiles.
5. The conclusions about the importance of radius of action of defense weapons, namely that
   a. The effectiveness of interceptors is insensitive to changes in combat radius from 150 to 350 miles.
   b. The preferred radius of action of an area-defense missile is not critical and depends on quantities which can only be roughly estimated at the present time, so that it cannot be stated more precisely than as being in the range of 100 to 500 miles.
   c. The relative numbers of local-defense missiles and area-defense missiles (of equal single-shot kill probability) which have to be on hand to achieve the same defense strength is in the range of 2:1 to 4:1.
6. The numerical conclusions which were reached about the relative effectiveness of the many weapons investigated for the defense of the United States. These conclusions are stated in Sec. IV (page 23*ff*). They are expressed in terms of estimates of over-all attrition and cost. These studies took into account theoretical estimates of weapon performance, operational degradation factors, tactical questions, etc., and were made in an over-all operational environment involving the United States target system. One result of this type of study is the realization that a large fraction of the cost of a weapon program lies in the direct and indirect personnel costs, so that improvements can sometimes be made by changing maintenance procedures, degree of automatization, reliability, etc., which outweigh changes in more obvious characteristics of the weapons.
7. The conclusion that interceptors should employ multiple firing passes if at all possible. It was determined in this analysis that the additional cost of more radar coverage and interceptor endurance to achieve this was in many cases more than outweighed by the increased capability of killing enemy bombers.

8. The conclusion that a vigorous warhead research program is needed to extend our knowledge of the properties of fragments, blast pellets, and rods against modern bombers and advanced types of missiles.

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CHAPTER 3

GENERAL INTRODUCTION

A study of the defense of the United States against air attack could be oriented in a great many different directions. This chapter describes the directions taken by RAND's Air Defense Study in its choice of situations studied, in the types of questions considered, and in the methods of arriving at answers. Some of the main themes that turned out to be critical to defense planning are discussed. Because the RAND study used the systems-analysis technique to an unusual degree, some discussion is presented of this attempt to obtain numerical answers to problems involving very complex sets of interrelated variables. An indication is given of the limitations of the numerical approach, and of the complementary role of more conventional qualitative analysis.

I. Scope of Situations Studied

Early in the study it became evident that the very great variety of possible enemy and friendly strategies made it necessary to concentrate on some of the most likely situations. Other situations could then be explored to see if significantly different conclusions or recommendations would result. The choices of emphasis made were based on a judgment of the ability of RAND's team to make meaningful recommendations in the time available.

The study was primarily concerned with *active* air defense. The dispersal of plants and cities and the operations of civil-defense organizations were not studied directly. A detailed appraisal of the defense of the Zone of the Interior—the continental United States—was made, but the defense of forward bases in Alaska, the United Kingdom, and elsewhere was not considered in detail, although such requirements affected some of the judgments on weapon choice. Although the problems of defending such advanced bases might be quite different from those problems associated with the defense of the ZI, some parts of the present study could be useful in the investigation of advanced-base defense. In particular, some of the data on weapon characteristics, radar-coverage requirements, feasibility of low-altitude attack, and the effectiveness of low-altitude defenses are applicable.

DEFENSE DEPLOYMENT

Emphasis in the defense study was on cases in which defense units were deployed at or near the targets to be defended. That is, local-defense weapons were placed around target cities or industrial plants, and interceptors were based near the important cities or industrial areas. In keeping with this, radar coverage was primarily over the United States, with contiguous extensions of coverage a few hundred miles into Canada or out over the ocean.

This, of course, is only one of several possible ways to defend United States targets. Another strategy would be to deploy the defense weapons much farther from the targets in the expected direction of enemy attack. For this strategy, radar coverage would have to be deployed outward to alert these defense weapons. Even if the defense weapons themselves should be deployed at or near the targets to be defended, it is possible to envisage radar coverage in belts or localized areas away from the United States proper and in the expected direction of the enemy attack. These outward deployments of defense weapons and radar coverage were not considered in as great detail as were the target-based defenses and contiguous radar coverage. This was partly because a preliminary investigation indicated that it was less desirable to deploy defense weapons far away from the targets than to deploy them very close to the targets. For noncontiguous radar coverage, it was difficult to assess the gains that would be made by deploying such coverage far away from the United States in view of such expected drawbacks as the increased payoff of feinting attacks, vulnerability of the patrol to enemy attack, the difficulty of getting continuous coverage, and the ability of attackers to alter the direction of approach after they cross the outlying belt of radar.

TIME PERIOD STUDIED

As noted in Chap. 1, the time period of the study was from the earliest date at which a serious enemy threat is believed to exist until the date for which it becomes impossible to make meaningful predictions of weapon characteristics. The earliest date was estimated to be around 1953, which is also about the time when present Air Force programs will result in full operation of a radar network and interceptor squadrons. The latest date for which it was felt that predictions about weapons could be made was about 1960. There is a possibility that several generations of weapons and radars, having quite different characteristics, will appear during a time period as long as this. For example, we must expect the presently programmed equipment, plus, at most, minor

changes, to be in existence in the field in 1953, whereas by 1960 we can have equipment which is now in the early-development phase in the laboratory, or in some cases not even started.

This extended time period gave such a great number of possibilities in defense and offense weapons that a set of definite dates was picked to permit a systematic study of the air defense question. At each of these dates an enemy attack was postulated and our air defense effectiveness was evaluated. From these separate studies it was possible to draw general conclusions concerning the preferred line of weapon development and the desirable methods for its employment for air defense. The dates chosen were mid-1953, 1955, 1957, and 1959.

THE ENEMY ATTACK

The enemy attack was considered to consist primarily in the airborne delivery of atomic bombs on United States targets by the Soviet Union. The atomic bomb was chosen partly because it was felt to be a very likely weapon as well as a very effective one for damaging our target system. (Some consideration was given to attacks with RW, BW, nerve gas, and other weapons. It was realized that most of the conclusions about our defense weapons, our radar networks, and our long-term defense strategy would not be seriously affected if one of these other types of weapons were employed in the enemy attack.) The delivery of atomic bombs was assumed to be accomplished principally by manned aircraft, although a progressive capability in air-to-surface missiles was assumed, as was a capability in surface-to-surface missiles for the later years of the study. (See Chap. 5.)

The United States target system chosen for the present study was based on the assumption that atomic bombs would be used by the enemy. Among the targets considered were the large urban areas of this country, plants of strategic war industries, and SAC installations. These targets would still be essentially the correct ones to consider if the enemy attack was assumed to be made with RW, most forms of BW, or nerve gas. The basic target system is shown in Fig. 6 (page 11), and the subject is discussed in more detail in Chap. 4.

The study concentrated on an examination of the initial heavy atomic attacks with which the Soviet Union might initiate a war. It was assumed that the entire series of attacks would occur in a time period of a few months, at most. Early in the study it was concluded that this situation was dominant in the selection of defense weapons and policies. Therefore other situations were given secondary consideration and were found to affect only the qualitative

arguments and not the numerical calculations. This applies to initial "feeler" raids (which are possible but not necessarily probable or critical), to the build-up of defense weapons during the attacks, and to the recuperation of targets.

II. Types of Questions Investigated

In a subject as large as that of the air defense of the United States, there are obviously many types of questions which could be investigated, ranging from the broad policy-making questions, which are dealt with by the Joint Chiefs of Staff or by the President, down to extremely detailed questions on the design of a specific piece of equipment for an interceptor or radar being investigated in industrial or military laboratories. At the highest policy level the question would be: How much of this country's military effort should go into air defense? An adequate study of this problem would involve inquiring into alternative uses of our national resources for air offense, for Army and Navy activities, and even for political-economic measures. This is far beyond the scope of the present study.

An attempt was made, however, to evaluate, for various levels of budget in air defense, the attrition which we might be able to inflict on an enemy attack and the damage which the enemy could do despite this amount of attrition. This kind of evaluation is an important factor in high-level deliberations on the allocation of national resources.

Another kind of question—and one which was studied in detail—concerned the selection of preferred sets of weapons to be used in various years to give the maximum air defense capability for a given defense budget. This selection involves comparisons of such dissimilar weapons as light ground guns, interceptors, guided missiles, and so on. It also involves consideration of how our efforts should be divided between the information and control network on the one hand, and defense weapons on the other.

Once the kinds of weapons to be employed in air defense are selected, the next question is how these weapons should be deployed. This involves the determination of how far the information network should extend over the ocean and into Canada, where our interceptor squadrons should be located, which of our targets should be defended by local defenses, and how far out from the targets the local-defense weapons should be deployed. All of these were included in RAND's study.

When dates as far into the future as 1956–1960 were considered, it was realized that the kinds of weapons available for air defense were numerous and that their detailed characteristics had not yet been established. Hence, it was possible to seek preferred characteristics of an interceptor, a guided missile, or a radar system for these later years. Much of the effort of the present study has gone into this attempt. In particular, a study was made of manned interceptors, of missile and rocket armament for these interceptors, of local-defense missiles, of area-defense missiles, and of two types of radar system having preferred design characteristics. In order to establish preferred characteristics for the interceptor, for example, a large number of *possible* interceptor designs were determined, limited by basic physical principles and the extrapolation of development trends. These interceptors were then evaluated for a given budget in terms of the air defense objective of preventing enemy bombers from delivering their bombs on our targets, and a set of *preferred* interceptor designs was selected. Such a generalized study involved a variation of such things as the interceptor combat radius, maximum speed, combat altitude, maneuverability, and armament load. For each of these variations, the necessary physical characteristics of the interceptor—its wing loading, aspect ratio, sweepback, etc.—had to be examined. Besides these more or less continuous variations in the weapon characteristics, more sharply different choices of characteristics had to be made at times—such as whether the interceptor should have just one kind of armament or simultaneously carry two kinds, one for high and one for low altitude, or whether it should have quickly interchangeable armament.

In several cases, the sort of study just described pointed out the definite superiority of new-type weapons or radars over those which might evolve from present equipment. An important part of the study has been to make preliminary-design investigations of new developments which might make a big change in our defense strength. These investigations have included surveys of applicable techniques now under development and an attempt to uncover new and novel ideas that would bear on the problem. Some of the most important of these developments are discussed, and possible design details are given, in Chap. 12. Those included are:

- An interim way of obtaining low-altitude coverage to supplement the present radar network.
- A more advanced radar system that could afford substantial advantages, both in cost and in performance.
- Missile seekers and AI radar with low-altitude capability.

- A local-defense missile, with semi-active homing-all-the-way guidance, that would increase our total defense strength.

III. Main Themes

Among the many problems examined, a few main themes stood out. These were:

- ***Seriousness of Low-Altitude Threat***

Enemy attacks at all altitudes, from the maximum combat altitude of the airplane considered down to the lowest feasible altitude, were investigated. This led to the realization that low-altitude attack is a very serious threat to this country and that low-altitude defense capability is difficult to achieve, since it involves some very complicated technical questions in weapon and radar-network design. This formed one of the main themes of the study over the entire time span.

- ***Effects of Weapon Radius***

Both area- and local-defense weapons, and Air Force and Army weapons, were considered in the defense of the country. Area weapons with a wide range of combat radii were considered. An attempt was made to evaluate how much more useful for defense a long-range weapon might be than a short-range weapon, other things being equal. This has a direct bearing on the preferred combat radius of interceptors as well as on the comparative capabilities of short-range local-defense weapons and interceptors for defending our target system. It was found that the increased effectiveness due to greater combat radius is much less than has been commonly attributed in previous investigations of long- and short-radius weapons.

- ***Variety of Threats***

A wide variety of offensive threats was considered. Bomb carriers varied from the slow TU-4 bomber up through supersonic air-to-surface and surface-to-surface missiles. Tactics included a wide range of attack altitudes, visibility conditions, and concentrations of attack. This resulted in many possible combinations of cases to be considered, particularly when the capabilities of many different defense weapons were assessed. It was quite frequently found that no one or two weapons, but only combinations of defense weapons, would do the whole job.

• *Interaction between Radars, Interceptors, and Local-Defense Weapons*

The interaction between radar coverage and the effectiveness of interceptor and local-defense weapons was investigated. As the extent of radar coverage was increased, greater use could be made of interceptor weapons because of the increase in time for air-to-air combat and for deploying interceptors over greater distances to protect more targets. A compromise was found between the increased cost and difficulty of extending the radar coverage and the increased effectiveness of interceptors so achieved.

IV. The Defense Systems Analysis: The Study's Numerical Phase

In order to recommend preferred design characteristics of interceptors, guided missiles, and other parts of the defense, it was apparent that quantitative studies would have to be made. Once such studies were started it was found that their scope had to be expanded to give a meaningful answer, even for specific design characteristics. For example, to recommend a preferred interceptor combat radius, it was necessary to study interceptor performance characteristics and cost as a function of combat radius. It was also necessary to determine how much more effective a long-combat-radius interceptor is than a short one. This involved a study of the United States target system, a study of the possible pattern of enemy attacks, and a study of the amount of radar coverage needed to utilize longer-combat-radius interceptors. This led, of course, into the study of the costs of radar coverage, the proper deployment of radar, and so on. To be sure that the answers obtained were sufficiently general, it was necessary to consider different interceptor armaments to see if they would affect the answers. This required, in turn, an analysis of the air battle between interceptors and bombers and a determination of the attrition of interceptors and bombers in such a battle. The question of whether the preferred combat radius of an interceptor would be affected by the presence or absence of local-defense weapons resulted, naturally, in a study of the capabilities of these weapons.

The final conclusion was that one complete quantitative analysis would have to be made of the whole air defense problem, including the characteristics of interceptors, guided missiles, guns, radar networks, enemy tactics, the United States target system, and all the other relevant factors. *This quantitative study is called the Defense Systems Analysis.*

This approach to the air defense problem is rather novel. Many instances have arisen in recent years, particularly in the operations of government, the Armed Forces, and large industry, in which it appeared that quantitative scientific analyses should have broader bases to be really useful. Because the RAND Defense Systems Analysis took into account, in a mathematical framework, an unusually complex array of interrelated factors, some discussion of its advantages and disadvantages is given here. The disadvantages, being less obvious, are treated more extensively. Thus, the study yielded, aside from its direct aims, some knowledge of the useful breadth of quantitative studies of Air Force problems.

An idea of the scope and interrelation of the parts of the systems analysis is shown diagrammatically in Fig. 12 and its analytical components are prescribed in a flow chart (Fig. 13). This flow chart is a simplified version of one which was used in organizing the analysis. Each box represents a subproject; on some of the subprojects—such as those dealing with surprise and countermeasures—not much could be done. Others were treated at length and are reported in some detail in RAND research memoranda.[1]

One advantage of the systems-analysis approach is that it gives a better sense of perspective than might otherwise be gained. Variation in one equipment parameter might appear to be very important at first but turn out to be noncritical in the broader view. As mentioned in Chap. 2, this is just what happened in the case of interceptor combat radius over the range of about 150 to 350 nautical miles. Conversely, some of the other parameters turned out to be quite critical. It thus became possible to focus attention on the most significant variables. Another advantage of this method is the clarity with which lack of knowledge is pointed out. Facts which might be slurred over in a discussion must be pinned down in a numerical analysis.

The systems-analysis method also helps to establish the correct environment for more detailed studies. The aircraft industry, for example, has long felt the need for a better delineation of the uses and environments of new airplanes than that provided by intuitively derived military characteristics and specifications. If these starting points are made more realistic, then their detailed studies are more meaningful.

Finally, it might be said that the systems-analysis approach, being derived from the disciplines of mathematics and physics, encourages methodical and unbiased reasoning throughout the study, in both quantitative and qualitative considerations.

[1] These memoranda are listed in Appendix II.

V. Some Limitations of the Defense Systems Analysis

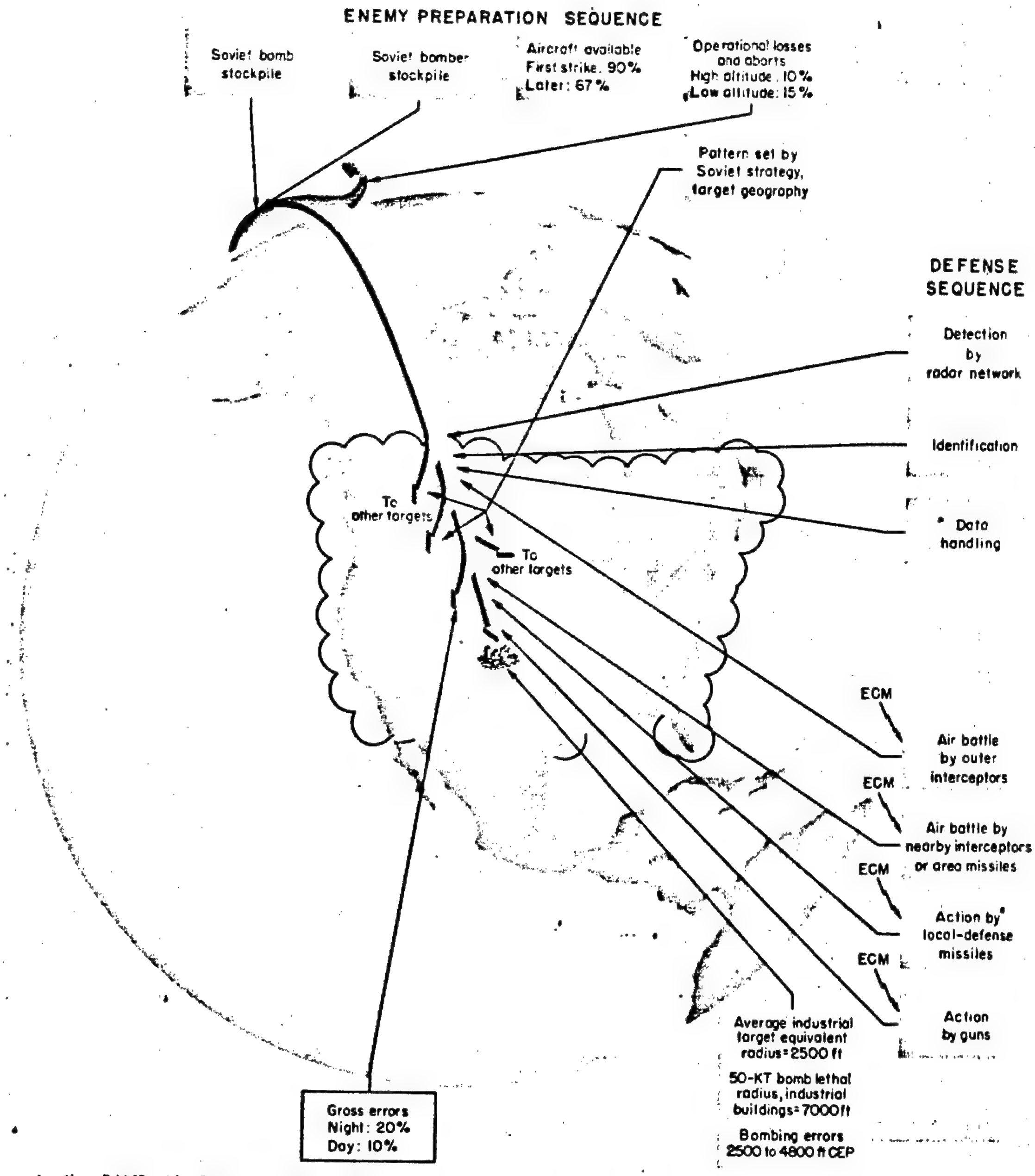
The systems-analysis approach, however, has some serious limitations. Some discussion of these points should help the users of the present study to gain an appreciation of the caution with which the numerical results should be applied.

FIELD PERFORMANCE

The actual operational performance of future weapons in combat cannot be obtained from a purely theoretical study of the weapon characteristics. Past experience has shown that in operational use weapons are seldom as good as predicted by theoretical estimates. This has led to the use of so-called operational degradation factors which express how much worse a weapon may be in combat than laboratory tests or a theoretical analysis would indicate. Limited information is available from operations-analysis studies of the operational degradation factors for some of the weapons used in the last war. Unfortunately, most of these factors could not be applied in the present Air Defense Study because the operational context is quite different and because the weapons considered are new and different. This difference becomes more and more noticeable as the years go on. For example, there is no experience from which operational degradation factors can be directly deduced for some of the future missiles. This difficulty introduces an element of uncertainty into the evaluation of the relative effectiveness of various weapons. This problem has been handled in the following way: First, theoretical estimates have been made of the ideal performance of each of the weapons of the study. Secondly, a best possible estimate has been made of the operational degradation factors to be expected from an examination of World War II data and from reasoning about the differences between World War II equipments and those being studied. Thirdly, these degradation factors are inserted in the present study and are spelled out specifically, where they are applicable, so that the reader is quite aware of what factors are being used. Finally, the study is so arranged that if desired, different degradation factors may be employed and the effect of these changes on the final answer can be determined.

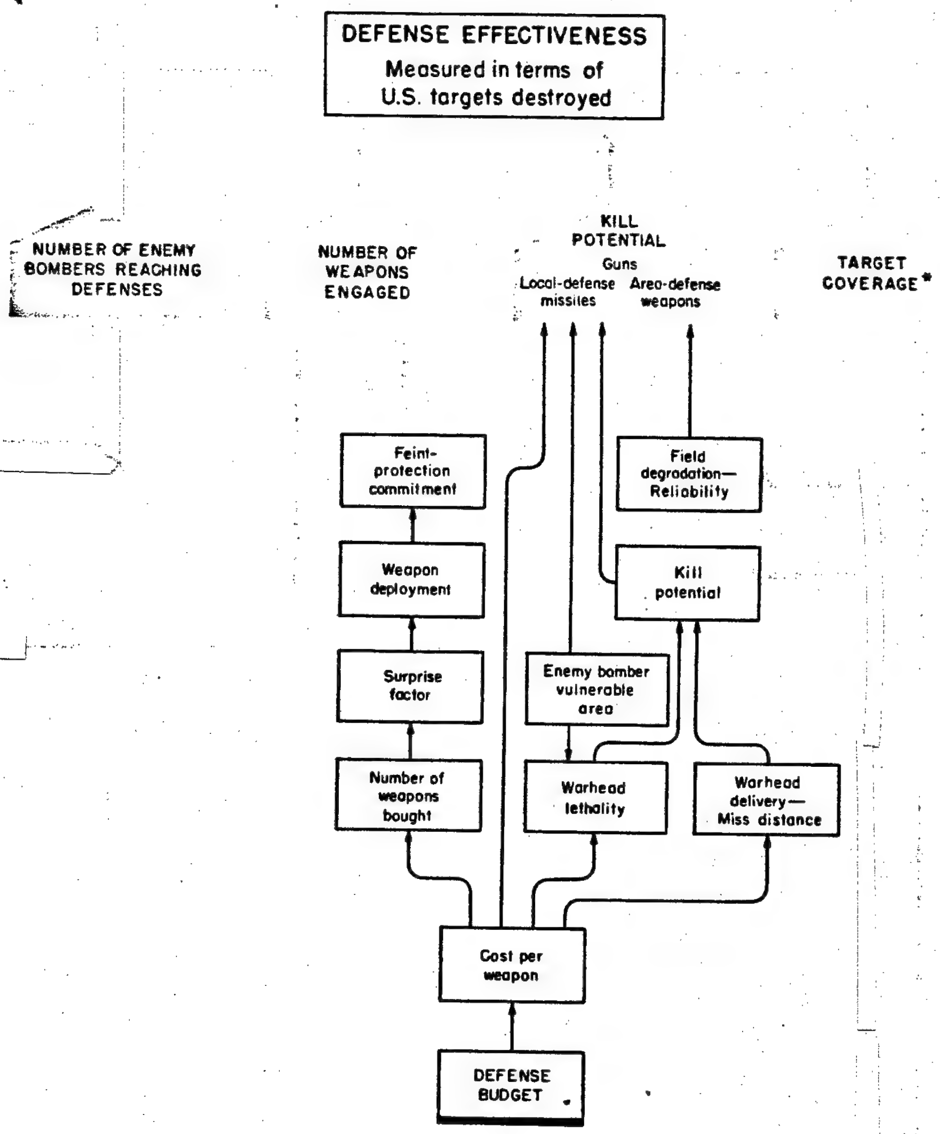
LACK OF DATA

For a part of the study it was found to be impossible to make a theoretical estimate of weapon capability, since no significant operational data exist. A



In the RAND Air Defense Study, defense was measured in terms of United States targets saved or destroyed. This diagram shows some (not all) of the factors entering into these computations.

Fig. 12—Factors affecting the



*Expected fraction destroyed with no defense:
Industrial—0.70 to 0.98 (depends on altitude and visibility)
Population—approximately 1.0

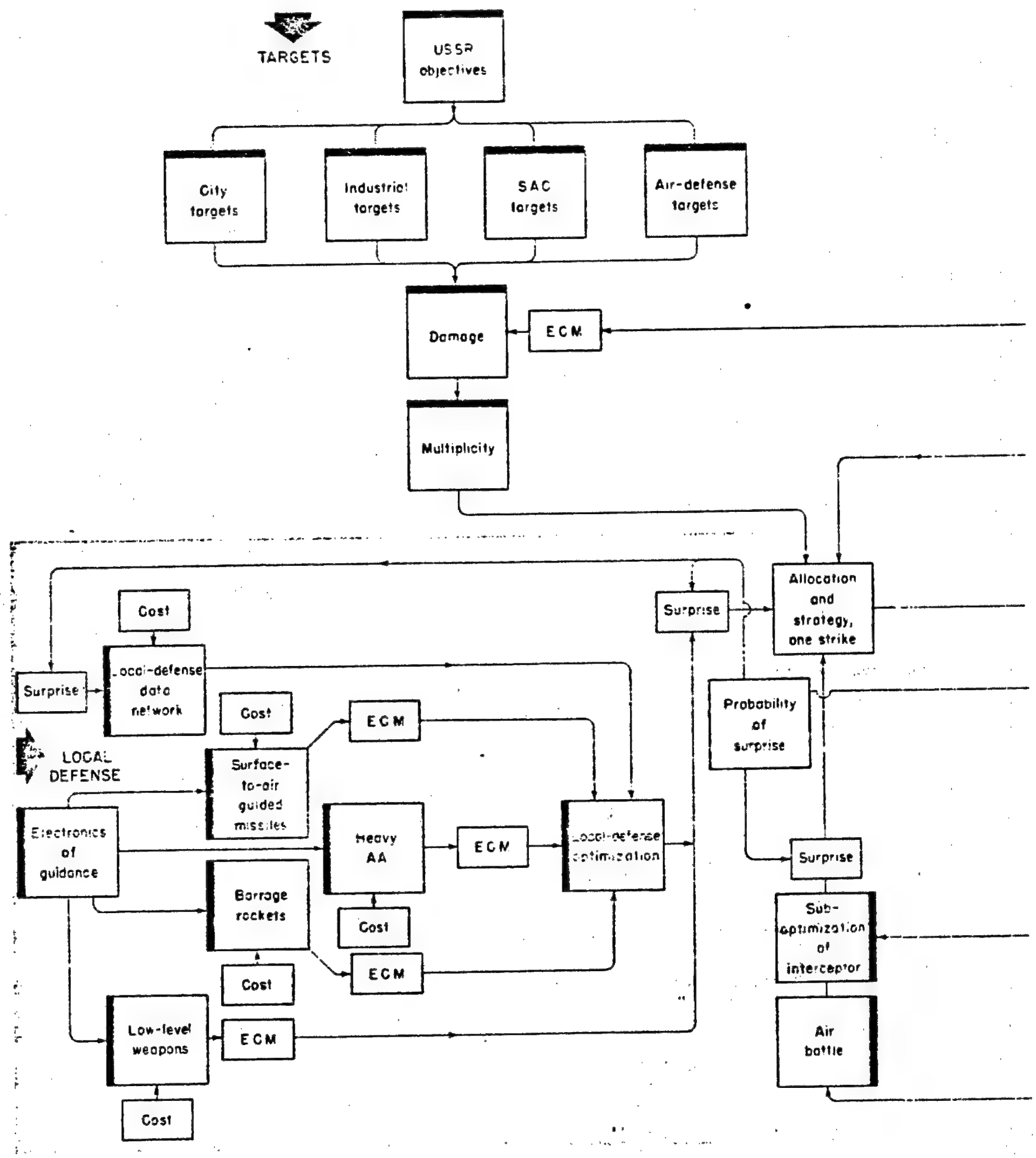
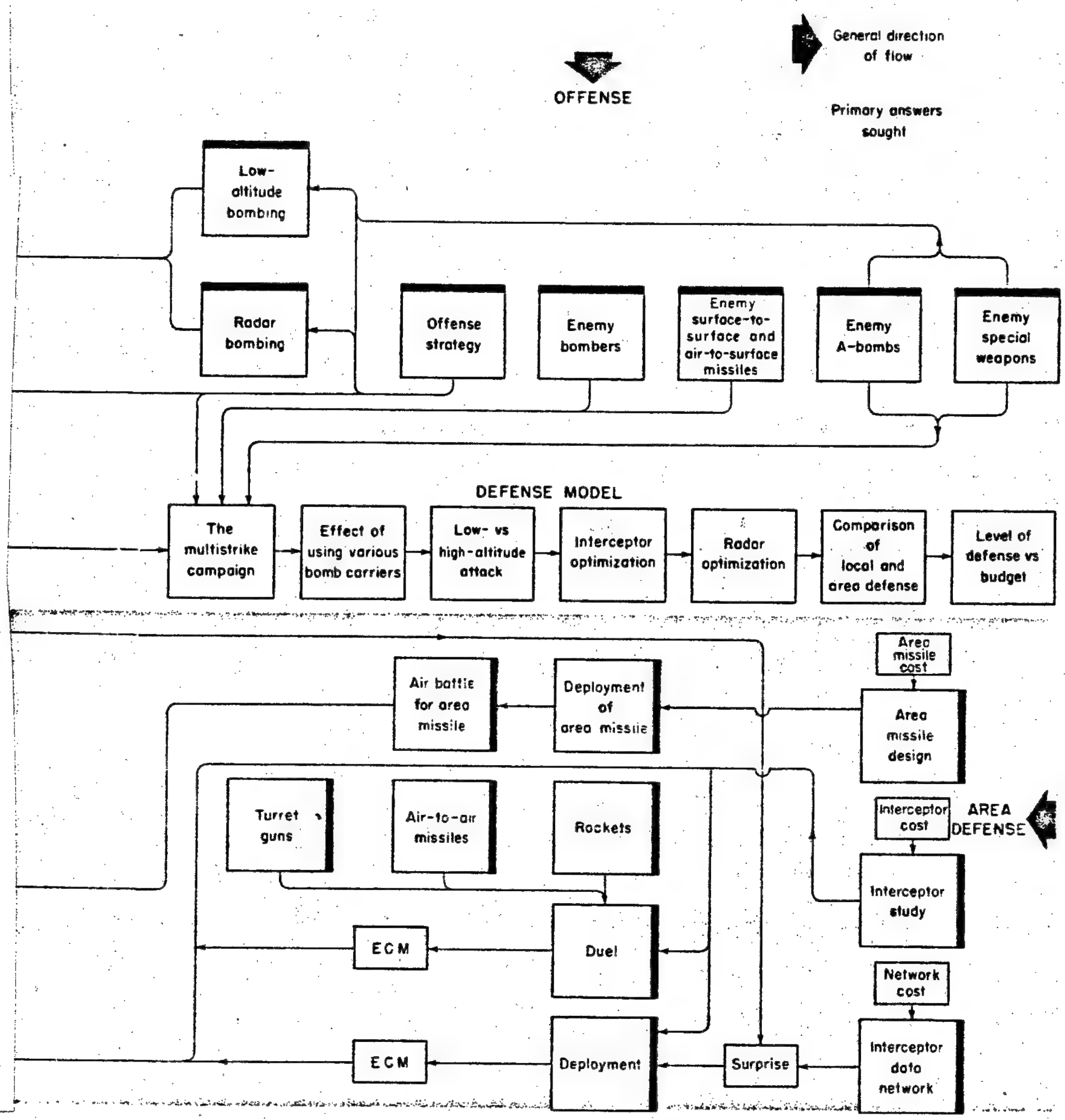


Fig. 13—Defense Systems Analysis flow chart


General direction of flow
OFFENSE
Primary answers sought
Low-altitude bombing
Radar bombing
Offense strategy
Enemy bombers
Enemy surface-to-surface and air-to-surface missiles
Enemy A-bombs
Enemy special weapons
DEFENSE MODEL
The multistrike campaign
Effect of using various bomb carriers
Low- vs high-altitude attack
Interceptor optimization
Radar optimization
Comparison of local and area defense
Level of defense vs budget
Area missile cost
Air battle for area missile
Deployment of area missile
Area missile design
Turret guns
Air-to-air missiles
Rockets
Interceptor cost
AREA DEFENSE
Interceptor study
ECM
Duel
Network cost
ECM
Deployment
Surprise
Interceptor data network

particularly troublesome example of this is the low-altitude capability of some high-altitude weapons. No theoretical way is seen, for example, to estimate realistically the effectiveness of an interceptor, variously armed and equipped with various AI radars, when it is operating at low altitudes in the presence of ground-clutter signals. Operational data from the last war are virtually non-existent, and operational data on the present interceptors are just now being collected. A similar uncertainty exists about some of the questions concerning the operational proficiency of some of the enemy forces; e.g., the ability of the enemy to navigate and to fly in formations cannot be estimated on theoretical grounds, and it is quite risky to impute present American operational capabilities to future Soviet military personnel.

FEASIBILITY UNCERTAINTY

There is a great deal of uncertainty as to whether ideas and techniques can be incorporated into equipment and tactics or whether they will turn out to be impossible by a given year. Of course, this uncertainty increases as the time period studied is extended farther and farther into the future. As an example of this problem, consider the question of the feasibility of low-altitude performance of air-to-air missile seekers. When will it be correct to assume that air-to-air missiles function as effectively at low altitudes as at high altitudes? When will airborne-moving-target-indication (AMTI) problems be solved, or new principles of missile seeker design be developed to this point? Another problem concerns the feasibility of airborne radar for early warning and control over land, where again the problem of ground clutter exists.

There are development programs now in existence seeking solutions to many of these problems, but the questions are: When will they bear fruit? and How well will they meet their objectives? These problems have been handled in the present study in two ways. First, in the systems-analysis part, it was decided to make the calculations as though certain development programs had matured and certain weapons had become feasible by the postulated date. For example, in some of the calculations it was assumed that the low-altitude capability of surface-to-air missiles of certain types would be achieved by 1957. *These calculations could be interpreted as showing the payoff if this development program is achieved.* A second treatment can be found in Chap. 12, where the feasibility of several of these developments is discussed in detail.

UNCERTAINTY ABOUT ENEMY CAPABILITIES

There is a large uncertainty about enemy capabilities. For instance, little is known about Soviet atomic bomb stockpiles, the development of more advanced bombers, the development of offensive missiles, and so on. The nature of enemy capabilities, on the other hand, will certainly make a tremendous difference in the preferred defense system. For example, if the enemy could not develop a satisfactory low-altitude-navigation and bomb-delivery technique, our low-altitude problem would not be a serious one, and a great many of the conclusions of the present study would be markedly affected. The procedure adopted in the present study was to make as reasonable an estimate as possible of the enemy capability, year by year, and to design our defense system in the light of these capabilities. Departures from these first estimates were then considered and our defense capability studied. The uncertainty about enemy capabilities puts a high premium on defense weapons which have flexibility and are effective against many kinds of attack. It puts a premium, for example, on an all-altitude defense capability and on high-speed defensive missiles for protection against a wide range of speeds of offensive weapons and carriers. Treatment of the nature of enemy capabilities had to be largely qualitative, since this remains one of the greatest uncertainties affecting preferred defense-weapon characteristics.

INTANGIBLES

There are many considerations which are obviously important in choosing defense weapons but which cannot be reduced to quantitative terms. For example, it is difficult to estimate the relative value of human life and physical equipment. Again, since area-defense weapons protect more kinds of things and more areas in the country than local-defense weapons could possibly protect, there is an indeterminate "bonus" value to an area-defense weapon. Also, some kinds of defense weapons, systems, or detection networks may be more vulnerable than others to such things as sabotage. There is no way to attach a numerical significance to this vulnerability. All of these intangibles must simply be borne in mind when deducing any conclusions from the quantitative study itself.

THE USE OF ELECTRONIC COUNTERMEASURES BY THE ENEMY

It has been found to be impossible to reduce the implications of electronic

countermeasures to a simple numerical degradation of the effectiveness of our defense weapons. This is partly because so many countermeasure possibilities exist for the enemy and so many counter-countermeasure possibilities exist for us in the design of our defense weapons that it becomes virtually impossible to predict which will actually be used in future years. Even for a given set of countermeasures and counter-countermeasures, the degradation in our defense weapons in an operational framework has usually been found to be impossible to evaluate numerically.

Countermeasures have been treated in the present study in several ways:

- Estimates have been made of the probable state of the countermeasures art year by year, showing the possible countermeasures which the enemy could employ at any given time. These probable enemy countermeasures were considered against the most likely defense weapons at each time period of the study.
- Desirable design characteristics of our defense weapons, which would tend to make them invulnerable to countermeasures, were estimated. As many of these as seemed feasible were adopted in the actual design of the weapons and form part of the conclusions and recommendations of the study. These design modifications would be reflected in increased cost and complexity of our defense weapons in many cases, and this increase in cost and complexity was taken into account in evaluating our defense capabilities.
- In many cases it turned out that there were possible enemy countermeasures against which we could not visualize any good defense. Some of these could seriously reduce our defense capability. These have also been enumerated and left as problems for further consideration. The whole question of electronic countermeasures is discussed in detail in Chap. 16.[2]

CASES NOT CONSIDERED

The scope of the study was so great that within the time available it was impossible to make a quantitative study of some combinations of defense weapons. For example, ramming interceptors and toss-bombing were not studied in detail. The extreme outward deployment of interceptors and radar systems, close to Russian take-off bases, was not studied in great detail, nor were

[2] Chapters 13 through 18 will be published separately as Part II of this report.

several schemes for advanced belts of early-warning or outpost-alerting radar. Possible use of infrared by either side was not considered to any great extent. Only a few preliminary probings into the possibilities of passive defense were made.

OTHER QUALIFICATIONS

Finally, it should be pointed out that in spite of a conscious attempt to avoid it, the decision to make a quantitative over-all systems analysis resulted in the devotion of a large amount of work to certain questions which later turned out to be relatively unimportant; consequently, less effort than might have been desired was available for studying the technical feasibility of some of the interesting defense weapons. One of the purposes of the present report is to explain the quantitative work that was done and to explain it in sufficient detail to permit other agencies studying the air defense problem to avoid duplicating it. Members of RAND's defense team are now engaged in more detailed design studies of items which were shown by the over-all study to be critical, and contacts have been established with Air Force agencies in an effort to pass on some of the specific lessons of the study.

* * *

In summary, it is felt that the limitations and uncertainties enumerated do not seriously affect the usefulness of the component studies. However, as the questions involved become broader and incorporate a higher level of complexity, the uncertainties introduced become greater, and confidence in the answer must necessarily be reduced. This is particularly true for such broad and general questions as the *absolute* amount of attrition to be achieved at various budget levels and the *absolute* comparison of quite dissimilar kinds of weapons. For example, it is felt that when dissimilar weapons are compared, one should be better than the other by at least a factor of three to five before the result can be considered significant. When preferred design characteristics of a single type of weapon are evaluated, however, much smaller differences are felt to be significant. Because of these limitations of a quantitative analysis, the present study should be considered to consist of two parts: first, a quantitative analysis, reported on in Chaps. 4 through 11 and 13 through 15, and secondly, qualitative discussions of technical feasibility questions in Chap. 12 and electronic countermeasures in Chap. 16. Finally, an attempt was made to draw together both the quantitative and qualitative discussions in developing the real conclusions of the study in Chaps. 17 and 18.

* * *

VI. Optimization Criteria

In making a quantitative comparison of different weapons in the systems-analysis part of the study, it was necessary to establish a criterion for determining a preference among weapons. This required a decision as to what job these defense weapons and weapon systems were to do and then a determination of which weapon or system was most satisfactory. The task was considered to be the protection of specific targets in this country against physical destruction by the assumed enemy attacks; i.e., all of our weapons were compared on the basis of how many United States targets would be destroyed after a full-scale enemy attack with atomic weapons. The "best" weapon was taken to be the one which would provide a given amount of protection to our physical targets for the least cost. This cost could be measured in several ways. For example, it could be the dollar cost of buying the defense weapons; it could be the manpower cost of manufacture or the manpower cost of operation in the field; or it could be the quantity of certain critical materials which go into the weapons.

The only measure of cost which has been developed with any degree of completeness in the analysis is the over-all dollar cost of a weapon program. This includes, among other things, the cost of the original production of the weapons, the cost of installing them in the field, the cost of operating them during their lifetime, the salaries of the men who operate them, the cost of living quarters for operating personnel, and the overhead costs involved. It represents the dollar cost to the nation of the whole weapon program. The use of this criterion of least cost in choosing weapons for the defense of targets in this country results, in several cases, in conclusions that are somewhat different from those that would be reached if other criteria had been used. For example, a large fraction of the dollar cost is associated with the manning of equipment. Hence, equipment designs which result in a cheaper initial purchase price are not necessarily dominant in the choice of a preferred weapon.

This cost criterion is somewhat unwieldy when detailed studies are being made of preferred weapon characteristics, and in some cases it was possible to choose a simpler criterion. In comparing two interceptor armaments, the cost of these armaments themselves is a quite small portion of the total interceptor-program cost, so it is sufficient to compare two similar armaments on the basis of the kill probability they would give for a given weight of installation. There are numerous other cases where the unit cost is quite trivial

and where the question concerns the desired characteristics and how they can be obtained. For example, the cost of installing moving-target-indicator (MTI) equipment on all ground radars in the present network would be an extremely small fraction of the entire defense-system cost, and yet it would make a noticeable difference to our defense capability. In such a case the problem is entirely one of finding the best way to get MTI.

On the other hand, there are some decisions for which it is imperative to introduce the economic consideration. In comparing a small high-performance interceptor with a larger interceptor having much more armament, it is obvious that, airplane for airplane, the large interceptor should be able to do a better job. But for a given total effort in production and for a given total effort in manning interceptor wings, a smaller number of the larger interceptors can be obtained. Therefore it is not clear which is the preferred interceptor until a comparison is made on the basis of cost *and* kills.

The total cost of any weapon program divides naturally into an initial cost, which includes the purchase of the equipment, its installation, and the initial training of the personnel involved, and a recurring annual cost, which takes into account the maintenance and operation of the equipment, its replacement, etc. In studying the costs of interceptor and radar programs, a complete year-by-year cost analysis has been made showing how great an initial cost and how great an annual recurring cost must be paid to carry out a given weapon program. This combined costing, however, is somewhat unwieldy when different interceptors or different radars are compared, and therefore a simpler unit of cost has been used in some parts of the study. This unit is called the *total annual cost* and is equal to the annual operating cost plus a fraction of the initial cost. This fraction is generally taken to be one-fourth, implying that the lifetime of the equipment is 4 years and that the initial cost is written off over its lifetime.

Another question which arises in comparing dissimilar weapons on a cost basis is that of *salvage value*. Suppose that a program were instituted in which a large number of interceptors were purchased for air defense. Suppose that shortly after their purchase the country was attacked and that these interceptors were used for their original design purpose of defending us from invading bombers. After the initial attacks were over, many of these interceptors would still be operational and could be used for defense of advanced areas, or perhaps they could be modified for use as tactical aircraft in land operations. On the other hand, large fixed radar stations probably could not be successfully salvaged for use elsewhere. Similarly, defense weapons such as guided missiles would largely be shot away during the initial period of enemy attack and could

not be "salvaged" for use elsewhere. This implies that the "salvage value" of the interceptor should be considered as a bonus in its favor. Numerically it is very hard to decide how large such a bonus should be, because the relative importance of the interceptor's use in the air defense of this country and its tactical use elsewhere is not at all clear.

As a practical solution to this dilemma, it was decided to cost all weapons on the assumption that at the end of the period of enemy attack a defense force would be on hand equivalent to that used during the campaign. That is, in the case of interceptors, those which were actually lost during the campaign would be assumed to be repurchased, and in the case of guided missiles, all of those shot away would be repurchased. This resulted in a requirement that for every missile bought for use in air defense, a second missile would be bought to be held in reserve for use after the initial campaign. The basic reasoning behind this choice was that it is not safe to assume that the requirement for air defense will no longer exist when the initial campaign is over, and that it will be necessary to maintain some sort of defense force in being for some time after the enemy attack.

Other measures of cost were considered in the present study. In particular, the number of trained men required for a defense system was felt to be a reasonable measure of cost. Some exploratory weapon comparisons were made on this basis. However, it was found that not enough information existed to use this cost criterion for all the weapons of the study, so it was usually necessary to resort simply to the dollar cost described above.

It should be pointed out once again that *this dollar cost criterion was only used in the quantitative analysis of the present Air Defense Study* and that considerations of manpower constraints and salvage value, as well as feasibility, vulnerability to jamming and sabotage, etc., were also used in reaching final conclusions and recommendations.

CHAPTER 4

TARGETS OF SOVIET BOMBING ATTACK

The location and character of the United States targets chosen for a Soviet bombing attack would determine many features of the plan of attack. Our expectation of which targets would be attacked is used in planning our defenses, but since some of our defenses are relatively immobile and are likely to be known to the enemy, his attack tactics would seek to minimize opposition. Therefore we tend toward the defense of those targets that we can least afford to lose.

In RAND's Air Defense Study is was necessary to select a system of probable targets for several reasons. For one thing, in the course of the analysis, *targets destroyed* and *targets remaining* could be taken as measures of the effectiveness of various defense budget levels, thereby permitting some conclusions regarding the possible effect of air attack on our ability to wage war. The same measure was used in comparing combinations of defense weapons. (See, for example, Figs. 10 and 11, pages 35 and 37.)

In another part of the study the target system was used in comparing weapons of different combat radii—heavy interceptors, light interceptors, surface-to-air missiles, and guns. In each case the fraction of our targets protected by a single weapon depends on the geographical distribution of targets and the protection radius of the weapon. As a part of this comparison, both the deployment of weapons and the extent of the radar network required must be adjusted to an economical balance.[1]

The target system, laid out on large-scale maps, was used in studying the most efficient deployment of light guns and short-range missiles around a cluster of aiming points for enemy bombs and in deciding whether a single missile-launching site could protect a whole city.

Not much more need be said about the usefulness of this estimated target system. In the following discussion, the probable types of target, the ways of measuring the damage to each, and some of the factors influencing the choice of particular targets will be noted. *This choice was made in the* RAND *study*

[1] These interacting factors, and the ways of optimizing them, are treated in Chap. 11, "Radar Networks," and in the chapters on synthesis in Part II.

on the assumption that the primary offensive weapon would be the atomic bomb. Finally, the particular target system used and some of its characteristics will be described.

I. What Kinds of Targets Might Be Attacked?

- ***Population Concentrations***

People, their homes, and the businesses that are associated with urban areas might well be selected as targets exemplifying one possible enemy attack strategy.

- ***Strategic Attack on War Industry and Government***

Another enemy objective might be the destruction of specific industrial plants and facilities, chosen because of their importance to the United States war effort. There might be several subsidiary objectives in such an attack, and the choice of targets could influence the immediacy of the effects, their duration, and the phases of the war largely concerned. Attacks on supplies, such as petroleum, might quickly reduce the effectiveness of existing fighting forces. Attacks on aircraft assembly plants and tank factories would reduce our ability to replace weapons lost in battle. Slower, but deeper, damage could be done by attacks on steel mills and copper refineries. Damage to our governmental centers and transportation system would hamper our mobilization for war and generally disrupt planning and control.

- ***Urban-Industrial Concentrations***

Attacks launched against concentrated industrial facilities in urban areas might reduce the general level of our industrial capabilities. Such attacks would inevitably result in civilian casualties and destruction of homes; the proportion of industrial workers among those killed or injured would be high. In this type of attack it is assumed that the enemy would not be seeking to destroy any particular segment of industry.

- ***Strategic Air Facilities***

Attacks might be directed against the airfields, bombers, bomb-fabrication plants, and depots, all of which make up the United States atomic striking force. An attack on such a target system would be designed to prevent us from launching a major atomic counterattack.

● *Air Defense Installations*

An attack might be launched against the radar sites, picket ships, interceptor fields, gun and guided-missile emplacements, etc., which comprise our air defense forces. An attack on these targets would presumably seek to weaken our defense preparatory to an attack on one or more of the other target systems. It seems clear that an attack on our active air defense installations would not be justified if our air defense capability is very low or, in some cases, if our defense installations are so located and so constituted as to make such an attack as difficult as an attack directed against primary targets.

* * *

Detailed studies were made of two of these five target categories: population concentrations and war industry, and, to a lesser extent, strategic air facilities. The results are presented in Secs. II through V.

The urban industrial target system was not studied separately because it is felt that this system falls between the two major categories studied in its effect on the choice of defense weapons and tactics. However, one strategy considered was the indiscriminate attack on concentrated clusters of war industries without regard to their strategic importance. Targets were used from the war-industry category mentioned above. It is felt that this strategy approximates an attack on urban-industrial areas well enough for us to study the effect on defense-weapon choice.

Strategic air facilities, as a target system, were studied in the sense that they were laid out on the target maps, and interceptors and local-defense weapons were considered to be deployed to defend them. Difficulty in finding a good criterion of damage, as discussed below, prevented this type of target system from being used separately in the measurement of defense effectiveness versus budget or in weapon comparisons. For most purposes, SAC targets were considered in conjunction with war-industry targets.

Air defense installations were not specifically considered as a target system in this study except in the following indirect ways:

1. Local-defense guided-missile installations are so near to the targets they defend that by the time the bombers can attack the missile defenses, they may as well attack the targets themselves. It was assumed in the study that when the target is destroyed, the associated local-defense weapons are also destroyed.
2. The interceptor fields, area-defense-missile bases, and most radar stations are defended at least by the area defenses themselves. For this

reason, and because of their numerous and dispersed sites, many of which are not easily distinguishable, these area defenses did not seem to be very likely targets for a full-scale attack. It was assumed in this study that area defenses are weakened during an attack by the loss of interceptors shot down and by the expenditure of missiles fired at bombers.

3. Low-altitude gun and rocket defenses present a different problem. Here the weapons are considered to be deployed in a ring around the target. This gives the offense the chance of "blasting" a hole in the ring through which other bombers may penetrate unscathed to the desired target. This possibility is discussed in more detail in Chap. 16, Part II.
4. An attack directed against our ground control intercept (GCI) or tracking radars by small homing missiles with HE warheads presents a different type of problem. This possibility is discussed in Chap. 16, Part II.

An attack on industry generally, or on urban-industrial areas, is sometimes called "horizontal." An attack on selected industries making a large fraction of certain items essential to our war machine is called "vertical." SAC facilities and air defense installations are essentially vertical target systems, whereas population targets are essentially horizontal. The vertical systems have a characteristic effect of forcing the offense into an attack pattern which is geographically dispersed. In some horizontal attacks, however, the offense can concentrate its attack, never coming in contact with a large fraction of the defense weapons. In most of the synthesis work of the RAND study (to be described in Part II) it was found advisable to compute cases for both population and strategic attack on war industry, since the variation in the effect on results was usually considerable.

II. Measuring Damage

It is possible to make meaningful calculations of physical damage for various numbers of bombs delivered and conditions of delivery. Relating this physical damage to our national war-making potential, to our will to resist, or to our long-term national objectives is a much harder thing to do. It is also quite difficult to assess bomb damage in terms of human casualties. RAND's Defense Systems Analysis (the numerical part of the study) estimated *physical damage*

and used that as a way of comparing combinations of weapons or deployment strategies. Use of these numerical results to measure our war-making potential may be less reliable; nevertheless, these values are of interest as factors entering into decision making.

DAMAGE TO POPULATION TARGETS

Several effects of an indiscriminate bombing of population targets can be listed:

- *Psychological.* One or two bombs on a city might create panic and cause people to flee the city, thus rendering its industrial and other facilities temporarily inoperative. The magnitude of this effect would depend on the preconditioning of civilians to the real hazards of an atomic attack.
- *Physical destruction.* A *number* of bombs (ranging from about ten for New York City to one for most other cities) would be sufficient to destroy a majority of homes. This would create immediate problems of shelter, sanitation, and distribution of food and would produce a more permanent and serious effect than mere panic alone.
- *People wounded or killed.* A sufficiently heavy attack would injure a large number of people, make them unfit for work, and create a burden on the uninjured members of the community. To wound or kill a large fraction of the people in a city would probably require more bombs than in the above cases. Air-raid shelters, warning, disaster teams, and other vigorous civil-defense measures could play an important role in minimizing this effect.

RAND's study indicated that the number of bombs needed to disrupt a large fraction of the urban areas of the United States would be roughly as many as would be required to do serious damage to a major industry, such as steel or petroleum. The kinds of destruction accomplished in the two cases are quite different, and it is difficult to decide which would weaken our war-making capacity more, or be more desirable from the point of view of the enemy. Since arguments could be advanced in favor of either strategy, both were considered in the present study. The criterion of damage to the population centers was taken to be the destruction of homes and was expressed in terms of numbers of people made homeless. This was felt to be a more definite measure than

numbers of people wounded or killed, because of the possible mitigating effects, generally unpredictable, of advance warning and other civil-defense measures.

It should be pointed out that the attacks on population concentrations discussed here are quite different from the area-bombing attacks made on Berlin, Hamburg, and Augsburg in the last war. The U.S. Strategic Bombing Survey concluded that these had no great effect on the war-making capacity of Germany. Atomic attacks on the United States could do much greater damage to any single city, and many cities could be attacked simultaneously, precluding assistance from neighboring cities. The total weight of attack on population centers visualized in the present study is roughly equivalent to the dropping of one or two million tons of HE bombs in a single raid (as compared with 8600 tons of bombs dropped in the Hamburg raids during July and August of 1943).

DAMAGE TO WAR INDUSTRY

Physical destruction of the industrial buildings in attacks on an industrial target system would be sufficient to cause most production to cease during the initial phase of the war. RAND's study used only this measure and did not consider the damage to machinery inside the buildings or the problems associated with replacement of manufacturing facilities.

[illegible]	[illegible]
Petroleum plants	5,100 ft
Steel plants	5,900 ft
Heavy steel frame	5,900 ft
Light steel frame	9,500 ft
Load-bearing brick	11,000 ft
Wood frame	16,000 ft

In the calculations of damage achieved in attacks on miscellaneous industrial targets, the structures were estimated to be a mixture of light steel frame and heavy steel frame. A lethal radius of 7000 ft was used, except for the steel and petroleum industries, where the values listed above were used.

[*] These data are based on the official expected-target-damage estimates in use at the time that this study was made.

The average configuration typical of American industrial facilities was estimated to be equivalent to a circular target 2500 ft in radius.

DAMAGE TO STRATEGIC AIR FACILITIES

It was found to be extremely difficult to measure damage to our strategic air facilities for purposes of analysis. The problem is complicated by the ability of the bombers to take off if enough warning is given. The fraction of the SAC force getting off and the fraction carrying self-sustaining equipment would depend on both the state of readiness and the length of warning. Further uncertainties enter into any realistic consideration of SAC facilities as a target system because of the possibility of nonaerial attacks, e.g., sabotage. Therefore, no attempt was made to consider strategic air facilities as a *separate* target system.[3]

BOMBING ERROR AND BOMB COVERAGE

The Soviet bombing forces were estimated to have the following capabilities in bombing typical SAC or industrial targets. (This is discussed in more detail in Chap. 5.) Circular error probable (CEP) is the radius of the circle, with its center at the aiming point, which is expected to enclose half the bombs dropped. Gross errors are excluded.

Condition of Attack (on Industry or SAC)	CEP (ft)	Gross Errors (%)	Aborts and Operational Losses (%)
High altitude, night	4800	20	10
Low altitude, night	3600	20	15
High altitude, good visibility	3000	10	10
Low altitude, good visibility	2500	10	15

For attacks on large urban areas, the exact value of the CEP was found to be unimportant in several test calculations. In the population attacks considered,

[3] Calculations of possible physical damage to SAC facilities and consideration of the defense of SAC installations have been made by Operations Analysis Section, HqUSAF. See OAS Study No. 4 and Special Report No. 6 (both Top Secret).

bomb coverage was taken to be complete (see below), and only gross errors and operational losses were taken into account. For selected cities the lethal radii against the several types of structures were used in conjunction with maps of the cities showing the predominant structure pattern and density of dwelling units, and the number of people made homeless was determined for each bomb assumed to be dropped. These maps of building types were only available for New York, Washington, and Los Angeles; judicious interpolation extended the results to other large cities. Figure 14 shows the damage to New York. Curves showing the number of people in the cities bombed and the number made homeless, as functions of the number of bombs dropped, are given in Fig. 15.

In the case of industrial bombing, where specific targets are attacked, it is convenient to define a quantity called "expected coverage," the expected

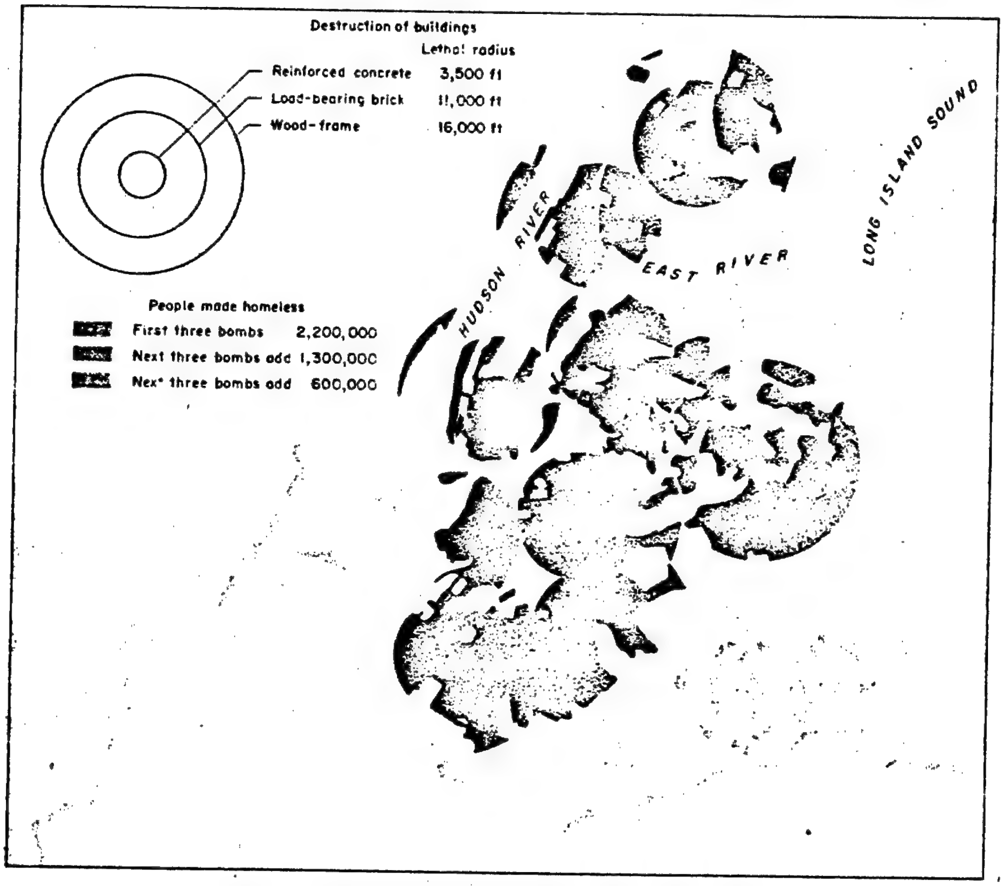


Fig. 14—People made homeless in New York City

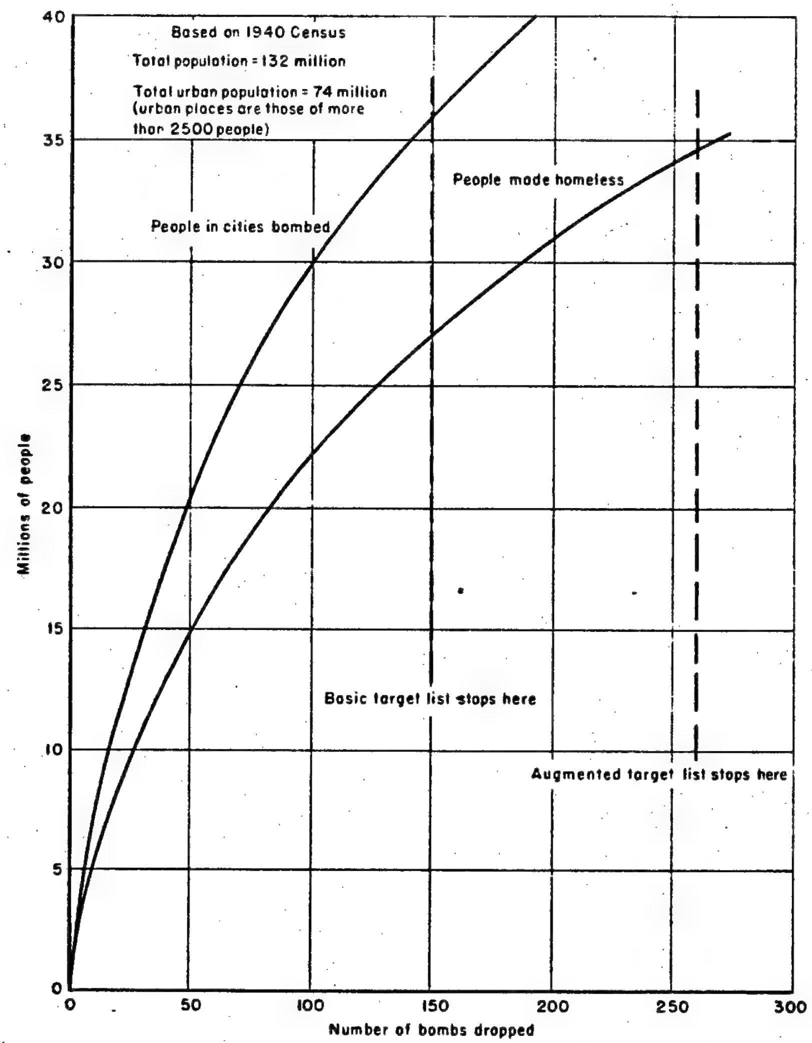


Fig. 15—Cumulative urban population versus number of bombs dropped

fraction of the target area destroyed when many such targets are attacked.[4] It does not include the effects of gross errors or losses. For the CEP's given above and the 2500-ft effective target radius, the following expected coverages obtain:

	Expected Coverage
High altitude, night	0.70
Low altitude, night	0.87
High altitude, good visibility	0.93
Low altitude, good visibility	0.98

These coverages, together with gross-error and operational-loss values, can be used to determine the number of *undefended* targets destroyed for a given target strategy and bomb stockpile. The *number of targets destroyed without defense* was a useful reference level in the weapon-comparison calculations and permitted the consideration of *targets saved* by the defenses studied.

IV. Factors Influencing the Selection of Targets

The target list used in the RAND study can be thought of as an "approved-in-advance" list compiled by the offense; for each target there would be a digest of aerial photographs, production data, and espionage reports. As each strike plan was developed, the strike targets would be drawn from this list to fit the desired strategy. The list would include only targets likely to be a part of some strategy. The number of targets on the list would therefore depend on the bomb stockpile assigned to the attack on the United States and the attrition expected to be achieved by our forces. (If attrition were high, it would be better for the enemy to concentrate on a few targets of a war-industry system, thereby ensuring serious shortages of a few critical materials, rather than to distribute the damage over more types of industry.) Some of the factors taken into account in the selection of targets are discussed below. In some cases these factors have been given distinctive names, or their names have special meanings in this context.

- ***Unequal Value***

Our targets differ in value over a wide range, both from our point of view and from that of the enemy. For example, there is more than a 10-to-1 difference in the number of people made homeless by the first and 150th bomb dropped on population targets. A similar variation exists between large and small steel plants.

- ***Multiplicity***

As mentioned at the beginning of this chapter, the Soviet Union can concentrate on some particular attack strategy that is unknown to us in advance.

In general, the effectiveness of any capability for physical destruction possessed by the USSR will be greater if it is concentrated on a few industries or on population than if only a few plants in every important industry are bombed and only a few of the largest cities. However, the cost to the United States of defending all towns, and all but the least important installations in all industries that might possibly be attacked, would be prohibitive. The best that the United States defense can do is to defend the major cities and the most important plants in those industries that are most vital to our economy. The fact that the offense can select a particular industry and attack "down the line," whereas the defense is limited to protecting the "top of everything," is a fundamental consideration of strategic air war. The need for the defender to defend more targets (if he is to survive) than the attacker may have to attack (to cripple the enemy economy) has given rise to a concept sometimes called "multiplicity." Considerations of multiplicity are central in the selection of a target list which gives a fair comparison of the effectiveness of local and area defenses.

- ***Overlap***

On the other hand, although "multiplicity" is a drain on any defense, "overlap" provides substantial relief. The defenses established to defend one city or plant may very often provide a common umbrella for the defense of other important cities and plants. The local defenses erected to protect one target will usually defend a circular area of 10- to 30-mile radius. For example, defense of the fifty most populated cities of the United States would incidentally involve the defense of numerous large steel, chemical, and petroleum facilities. The RAND study made detailed compilations of overlap, using maps of its target list.

- ***Flexibility***

Closely related to multiplicity (a target-system characteristic) is flexibility (a defense-weapon characteristic). A defense system is flexible to the extent that it can rapidly be redeployed in another area to defend different targets. The importance of flexibility depends on the degree of overlap: *if* the overlap in a target system is very great (i.e., if by defending, say, cities, a large fraction of every important industry is incidentally defended), there is no need for flexibility, and area and local defenses can be immobile. Flexibility may, during a long campaign, mitigate some of the problems raised by multiplicity. After one or two raids it might be possible to surmise the attack strategy of the Soviet Union and redeploy United States defenses accordingly.

- *Substitutability and Complementarity*

The outputs of different industries tend, in varying degrees, to be either substitutes or complements. (Goods X and Y are substitutes if a decreased supply of X raises the value of a unit of Y; they would be complements if a decreased supply of X decreased the value of a unit of Y.) If the Soviet Union decides to attack industries rather than cities, it should attack plants that make substitutes rather than complements. For example, it is unlikely that they would attack airplane engine plants *and* airframe assembly plants. A successful attack on one of these target classes would greatly reduce the value to the USSR of an attack on the other.

V. Selection of Targets for RAND's Study

A complete understanding of these problems would permit the determination, for purposes of analysis, of the defense strength which should be assigned to each target in our economy (of course, many targets would be assigned zero defense strength) and of the strength with which each target should be attacked as functions of enemy bomb stockpile, CEP, gross errors, bomber stockpile, and defense strength. The treatment of targets of unequal value and of the concepts of multiplicity, complementarity, etc., was not taken into account quantitatively. Actually, the RAND study made a considered appraisal to determine which industries should be defended, and then, for each industry and population target system, it made another attempt to choose particular places to be defended. This was done on the basis of the available statistics and bearing in mind the expected size of the enemy bomb stockpile. Two such target systems were prepared:

1. A *basic* list, which was felt to represent the situation in 1954, when it was assumed that the enemy would have a stockpile of 150 bombs to be committed in an attack on the ZI.
2. An *augmented* list, applicable to later dates when larger bomb stockpiles and more powerful offensive threats would exist.

The basic target list contains practically all the most important war industries. The list was augmented to determine the effect of a larger enemy bomb stockpile.

The types of targets in the basic and augmented systems, together with production estimates, are given in Table 1. It will be noticed that some war industries are not on the target lists. They were omitted not because the United States war economy would be insensitive to the loss of target plants in these

Table 1

SUMMARY OF BASIC AND AUGMENTED TARGET LISTS

WAR INDUSTRY TARGETS

Target	Number of Aiming Points Included		Percentage of Total Industry	
	Basic	Augmented	Basic	Augmented
Aircraft industry				
Assembly	28	46	86	100
Jet engines	5	5	99	99
Piston engines	< 5	< 5	100	100
Propellers	< 5	< 5	100	100
Aluminum industry				
Alumina	< 5	5	96	100
Aluminum reduction	7	11	84	100
Cryolite	< 5	< 5	100	100
Antifriction bearing industry				
Ball and roller bearings	7	19	82	100
Cylindrical roller bearings	< 5	5	91	100
Needle roller bearings	< 5	< 5	100	100
Precision balls	< 5	< 5	100	100
Taper roller bearings	< 5	5	97	100
Armament industry	None	5	zero	(*)
A-bomb production	21	21	(*)	(*)
Copper industry				
Refining	8	12	89	100
Smelting	11	16	87	100
Electric-power production	None	14	zero	(†)
Electronics industry				
Electron tubes	18	37	78	95
Radios and radar	23	23	73	73
Explosives industry				
Ammonium picrate	< 5	< 5	93	100
Anhydrous ammonia	12	12	96	96
DNT	< 5	5	85	100
TNT	7	14	79	100
Pentalite	< 5	< 5	100	100
Smokeless powder	7	13	90	100
Tetryl	< 5	6	93	100
Fractional hp electric-motor industry	7	16	66	85

Table 1—continued

Target	Number of Aiming Points Included: Basic	Number of Aiming Points Included: Augmented	Percentage of Total Industry: Basic	Percentage of Total Industry: Augmented
Lead-concentrating industry	9	9	54	54
Iron and steel industry				
Coke	None	44	(‡)	90
Pig iron	None	50	(‡)	90
Steel ingot	41	59	79	90
Transportation	None	10	zero	(*)
Navy shipyards	None	10	zero	(*)
Petroleum industry				
Ethyl chloride	< 5	< 5	98	100
Ethylene dibromide	< 5	6	99	100
Sodium (metallic)	< 5	< 5	100	100
Tetraethyl lead	< 5	< 5	100	100
Cracked gasoline	None	69	(‡)	80
Refineries	61	89	70	80
Strategic Air Command	25	25	(*)	(*)
Vehicle industry				
Tanks and combat vehicles	9	9	(*)	(*)
Heavy trucks	6	6	74	74
Medium trucks	11	19	75	90
Light trucks	8	16	70	91
Washington, D.C.	3	3	(*)	(*)
TOTAL	351**	543**		

URBAN POPULATION TARGETS

Target	Number of Aiming Points Included: Basic	Number of Aiming Points Included: Augmented	Smallest City Attacked (with a few exceptions; 1940 Census): Basic	Smallest City Attacked (with a few exceptions; 1940 Census): Augmented
Cities	150	260	86,000 population	50,000 population

NOTE: In the industrial tabulation, industries having less than five aiming points are specified as < 5. Definite numbers were used in the study, however.

*Data are not available for calculating percentage destroyed.

†90 per cent in each of four areas.

‡Although this industry is not on the basic target list, considerable damage could be done to it by attacking a related industry which is on the basic list.

**These totals cannot be checked directly because sometimes a single aiming point is listed under several industries.

industries but because the loss of plants in certain other industries would damage the war economy more severely. To defend these "secondary" industries, except where defense overlap exists, would be to invite greater destruction of more vital war industries. The object of defense deployment is to minimize the maximum damage that can be inflicted upon the United States economy.

In addition, it is often unnecessary to include all the plants of a defended industry. There are many small plants that contribute insignificantly to the economy. Generally, industrial plants which contribute less than a small fraction, usually 1 per cent, of the total are excluded from the basic target system. Figures 16 and 17 show the cumulative percentage of output as a function of the number of aiming points for the steel and petroleum industries. Cut-off points for the basic and augmented target lists are indicated.

The 150 *population* aiming points of the basic target list included all the principal parts of the large cities and all the small cities having a population of 86,000 or more. These aiming points were in 100 different urban areas. The

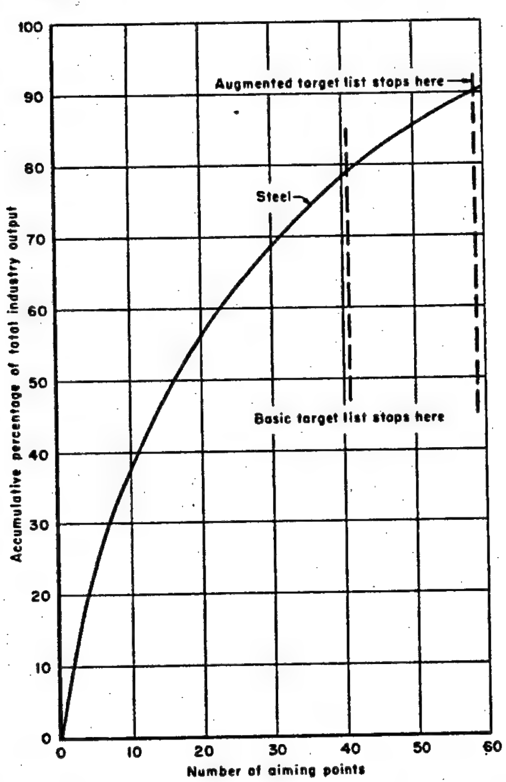


Fig. 16—Cumulative steel output versus number of aiming points

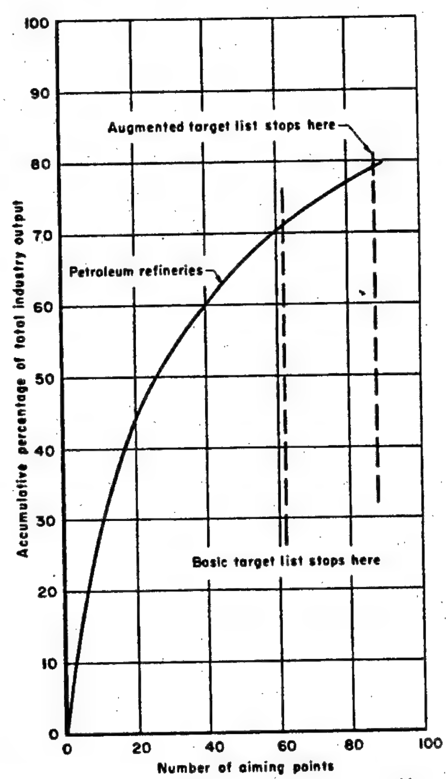


Fig. 17—Cumulative petroleum output versus number of aiming points

augmented list added 110 population aiming points. Figure 14 (page 74) shows the trend toward diminishing effect as the number of bombs dropped increases.

COMMENTS ON OMITTED TARGETS

Some specific reasons for omitting targets in particular industries, often believed to be vital, are given below.

- *The guided-missile industry* has been omitted because:
  1. At present it is in an experimental stage and the nature and location of future vulnerable components of the industry are not known.
  2. The industry will be so completely interwoven with the aircraft and electronics industries that it appears unlikely that it would be attacked separately.
  3. Although the present experimental facilities are important to the industry, they are unlikely targets because of the tremendous lag between experimental developments and field use.

- *The armament industry* (tanks and combat vehicles are treated separately) has been omitted from the *basic* list because:
  1. The United States has a large stockpile of small arms and light artillery, inherited from World War II.
  2. The industry is customarily on a stand-by basis during peacetime and is so organized that it can be expanded during wartime by conversion of industries manufacturing durable consumer goods during peacetime. However, because of the importance of the drawings and know-how concentrated in five government armament plants, these have been included on the augmented list.

- *The ammunition industry* (except for proximity fuzes, which are treated as electronics) has been omitted because:
  1. The industry is dispersed in thousands of plants during wartime.
  2. The plants could be easily replaced.
  3. There is a considerable stockpile of ammunition on hand.

- *Shipbuilding and repair facilities* have been omitted because:
  1. There is a large, well-dispersed fleet in storage.
  2. It is thought that shipbuilding and repair facilities would be relatively easy to repair or replace if destroyed, since they are principally assembly points for nearly finished materials.

3. Their physical vulnerability is relatively low.

- *Lead- and copper-mining facilities* have been omitted because:
  1. There are many widely dispersed mines.
  2. The mines would be difficult to destroy.
  3. Destroyed mining equipment could be replaced by similar mining equipment from gold mines and other nonessential mines.
  4. Mines account for only half the lead and copper supply. The lead-concentrating industry and the copper-smelting and refining industries are included on the lists.

- *The machine-tool industry* has been omitted because:
  1. Its destruction would not seriously affect war production for at least a year.
  2. There are numerous separate and small installations, constituting a poor set of targets.
  3. There is some production cushion, both in the industry itself and in nonessential industries.

- *Transportation facilities* have been omitted, except for certain iron-ore transport facilities on the augmented list, because:
  1. The extensiveness of the transport system, the large number of separate vehicles, and the number of alternative routes make effective interdiction difficult.
  2. Repairs could be effected quickly, so continual attack would be needed for prolonged interdiction.

- *The electric-power industry* has been omitted from the *basic* list because:
  1. There are thousands of well-distributed generating stations in the country, and in an emergency additional pooling of utility and private power could be effected.
  2. There is considerable production cushion, since almost half the power goes to nonessential uses. However, there are sufficient installations on the augmented list to include 90 per cent of the power production in each of four critical areas where there are only a few generating stations which are not interconnected by effective transmission lines.

- *Port facilities* have been omitted because:
  1. Their large size makes complete destruction uneconomical.
  2. Only half of their capacity is utilized.

3. Emergency facilities could be provided by loading from lighters.

- *Oil wells* have been omitted because:

1. They would be difficult to destroy.
2. The installations are widely dispersed within oil-producing areas. However, the oil-refining and aviation-gasoline industries are included.

- *Iron-ore mining facilities* have been omitted because they would be almost impossible to destroy. Certain components of the iron-ore transport facilities are included on the augmented list only; these bottlenecks can be by-passed by alternative transport facilities. *Pig-iron and coke production* are largely concentrated in locations producing steel ingots, which are considered more important because scrap iron can replace pig iron. Pig-iron and coke-producing facilities are included on the augmented list only. Major steel-ingot producers are included on both lists.

* * *

CHAPTER 5
OFFENSE CAPABILITY

The Soviet Air Force, during World War II, engaged in very few strategic-bombing operations. Emphasis was on the support of ground troops. There is still a preponderance of numbers in their tactical air forces, but there is every evidence that a high priority is being given to the development of the Long Range Air Force (LRAF).[1] Every aerial display brings out increasing numbers of four-engine bombers, many with radomelike protrusions. Indeed, it seems almost certain that Soviet planners, who have organized the prodigious effort that must be behind their atomic-weapon program, have also given equal attention to the entire machinery of an atomic strike.

As was mentioned at the beginning of this report, it is RAND's opinion that the Soviet LRAF will begin to have the potential for causing serious damage to the United States in about 1953. With that date as a boundary point, this chapter discusses the aircraft, missiles, and bombs that might be used and the tactics of their employment. The scarcity of reliable information on present Soviet activities has made this a very difficult task, and it has been necessary to make free use of imagination and projection into the Soviet viewpoint. The most important result of this projection has been the conclusion that low-altitude attack, possibly on a one-way mission, is a likely tactic of the Soviet LRAF. Another is the retention of United States strategic industry as a target system, together with population concentrations, in all parts of the study. In spite of the higher level of skill required for the strategic war-industry attack, it might seem particularly attractive to planners accustomed to focusing on national-production figures.

The chart of estimated availability dates for Soviet offense equipment is repeated in Fig. 18. Aircraft, missiles, and bombs, in turn, are discussed below, together with some possible tactics.

[1] This force is also called the ADD, after its Russian name.

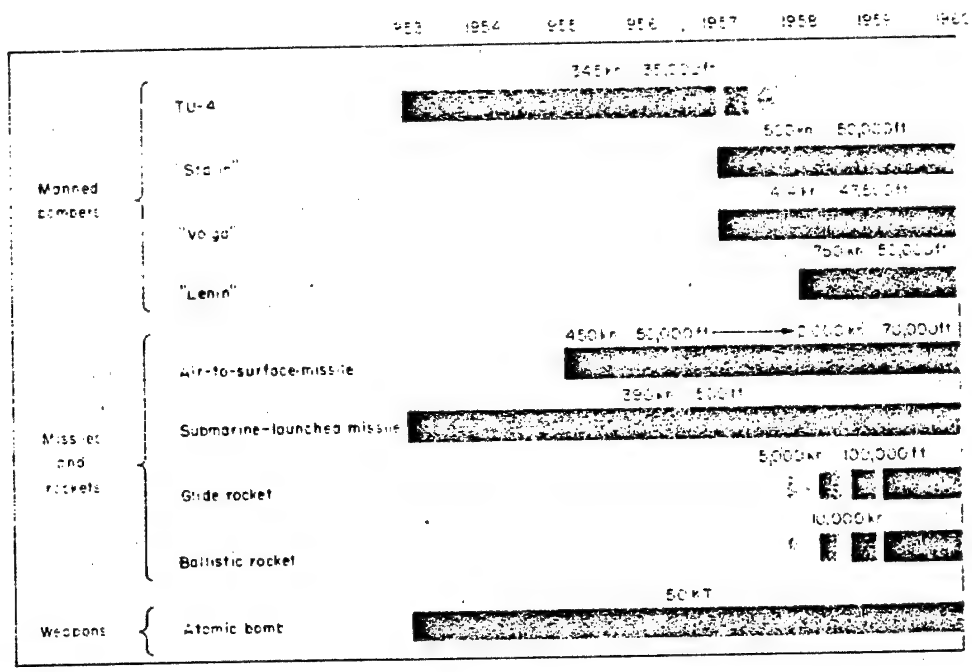


Fig. 18—Enemy offense capabilities

I. Aircraft Characteristics

The only strategic bomber on which there is reliable intelligence information is the TU-4, a copy of the USAF B-29. For the period of 1954 and later it is estimated that some improvements will have taken place, particularly in engine performance, so the characteristics of the aircraft for the present study have been taken to be approximately those of the USAF B-50D. This results in a target-speed capability of 345 knots at 35,000 ft or 265 knots at 2500 ft. The one-way unrefueled range of this aircraft is sufficient for attacks against most of the important United States targets from bases in Northern Russia, Siberia, or Eastern Europe. Two refuelings would be needed for round-trip missions to the great majority of our targets. This procedure is operationally difficult and would considerably reduce the size of the effective striking force if the tanker aircraft were drawn from the TU-4 stockpile. For this reason considerable attention is given to the one-way TU-4 threat in the 1954 part of the study. (A more detailed statement of TU-4 characteristics is given in Table 2;[2] a dis-

[2] *A note on significant figures:* In Table 2, and throughout this report, some of the values are given with a greater number of significant figures than is justified by the accuracy to which they

Table 2

ASSUMED ENEMY BOMBER CHARACTERISTICS

Russian Aircraft	TU-4	Type 31	Volga	Stalin	Lenin
Approximate U.S. equivalent	B-50D	....	Possible turboprop modification of B-47	B-52	Approximate speed threat specified for MX-1554 competition
Combat speed/altitude, knots/ft	345/35,000	310/35,000	414/47,500	500/50,000	750/50,000
Maximum speed at 2500 ft altitude, knots	265	....	280	420	565
Cruise speed/altitude, knots/ft	235/25,000	....	400/47,500	455/46,000	520/47,500
Radius unrefueled, nautical miles	2200	3500	3600	3100	1600*
Range unrefueled, nautical miles	4000	6500	~6700	~6000	~3100
Radius 1 refueling,† nautical miles	~3000	~4600	~4800	~4100	~2100
Range 1 refueling, nautical miles	~5200	....	....	....	~4300
Radius 2 refuelings, nautical miles	~3700	~5900	~6100	~5100	~2700
Initial gross weight, lb	175,000	225,000	170,000	400,000	200,000
Payload, lb	10,000	10,000	10,000	10,000	10,000
Number and caliber of guns	2/30 mm	2/30 mm	2/30 mm	2/30 mm	2/30 mm
Number and type of engines	4 reciprocating	(4 reciprocating ?)	4 turboprop	8 turbojet	4 turbojet with afterburning
Operational availability date	present	1952	1957	1957	1958

* With 200 miles at 750 knots.
† All refueled distances are based on refueling by an aircraft similar to the bomber.

cussion of routes, bases, and the effects of weather is presented later in this chapter.)

It is quite possible that the Russians have under development long-range strategic bombers of appreciably higher performance than the TU-4.[3] Unfortunately, however, there seems to be no definite intelligence data on which to base estimates of their characteristics. It thus becomes necessary to hypothesize one or more future Russian bombers. This has been done by using bomber-development trends in this country as a basis and these future bombers have been included in RAND's defense study to permit a test of United States defense-weapon systems against them. It is not anticipated that all of these bombers will necessarily be developed. The three bombers postulated are identified in this study as the *Stalin, Volga,* and *Lenin.*

The Stalin is assumed to be an aircraft similar to the USAF B-52. An availability date of 1957 is estimated, together with a target-speed capability of 500 knots at 50,000 ft altitude and 420 knots at 2500 ft. The range capabilities of this aircraft, being much greater than those of the TU-4, are such as to result in considerably lessened operational restrictions. (See Table 2.)

The Volga is an advanced turboprop airplane whose characteristics are taken from the RAND generalized bomber study.[4] This airplane is also similar, generally, to a possible turboprop version of the B-47. The pertinent characteristics assumed are a target speed of 414 knots at 47,500 ft altitude (average cruise speed of 400 knots), a gross weight of approximately 170,000 lb, and a combat radius of 3600 nautical miles; the availability date is assumed to be 1957. This airplane would be capable of round-trip unrefueled attacks against a large percentage of United States targets. Although having somewhat lower performance than the Stalin, this aircraft is physically smaller and less vulnerable. It was included in the study to observe the effect on defense-weapon choice of a change in bomber vulnerability and performance characteristics.

The Lenin is hypothesized as an aircraft having supersonic speed capability

are known, or by the use made of them. In the course of the study, which involved handling thousands of numbers and keeping track of changes and corrections, it was found that these extra figures served a useful purpose. They were "tags" which helped to identify the origins and revision status of the quantity. Since some of the users of this report may wish to follow through on some of the processing of data, or to check their origin in the supporting research memoranda, no deliberate effort has been made to round off numbers.

[3] Since this study was made, a new aircraft (Type 31) has been observed. Its characteristics are included in Table 2. It does not change the choice of defense weapons, however, since its estimated performance is comparable with that of the TU-4 except for its greater range.

in the target area. At present it does not appear feasible to achieve the required strategic-bombing distances with aircraft of this type without assistance. However, with assistance, as when carried initially by another aircraft, or when refueled, or through the use of advance bases, such an airplane could attack the United States. The characteristics assumed include a combat speed of 750 knots ($M = 1.3$) at 50,000 ft and a gross weight of approximately 200,000 lb. The estimated availability date is 1958. This aircraft was included in the study as the primary target against which a supersonic interceptor would be designed. Such an interceptor might have a dual requirement: for defense of the ZI and for defense of advance bases where a supersonic bomber might be a very real threat. Thus, although a complete investigation of the defense of advance bases was considered to be beyond the scope of RAND's defense study, consideration was given to the advance-base case in choosing the bomber threat.

II. Aircraft Numbers

Intelligence estimates indicate that there might be 1200 TU-4's in operational units by 1954. It was felt that some aircraft would be used for attacks in Western Europe, for mine-laying, etc., and that some would be held in reserve, so that *the number committed to one-way attacks on the ZI was estimated to be a maximum of 500.* This number was used in the study when mass attacks were investigated. In considering the other bombers it was realized that it might be possible to choose stockpile numbers reflecting the relative costs of building and operating these aircraft, as was done in the RAND offense bombing systems studies.[5] However, this was considered to be an unjustified refinement for the present study. A nominal bomber stockpile of either 150 or 500 was used for all types of bombers; 500 was considered to be a maximum and 150 was thought to be representative of the smallest stockpile for a decisive attack. It was found that the results for mass attacks are sensitive to the choice of a maximum bomber force in that this directly affects the estimates of the percentage of attrition any given defense can achieve and the estimates of whether the control capacity of a given radar network is adequate. The preferred types of area- and local-defense weapons and their preferred characteristics, however, are much less sensitive to the bomber-stockpile size. The analysis was arranged

in such a way as to facilitate rapid estimates of the effect of changing the size of the bomber stockpile.

III. Aircraft Armament

All enemy bombers were assumed to have twin 30-mm tail turret guns only. This assumption was based on an investigation of the effectiveness of all-around armament in protecting the bomber.

An exploratory study was made of a bomber with ten 50-caliber guns, of which six could bear at any one time, and the probability of survival of a rocket-firing interceptor was determined as a function of its angle of approach. This armament was found to be relatively ineffective in killing fighters attacking from the forward hemisphere.[6] (See Fig. 19.) Furthermore, the interceptors

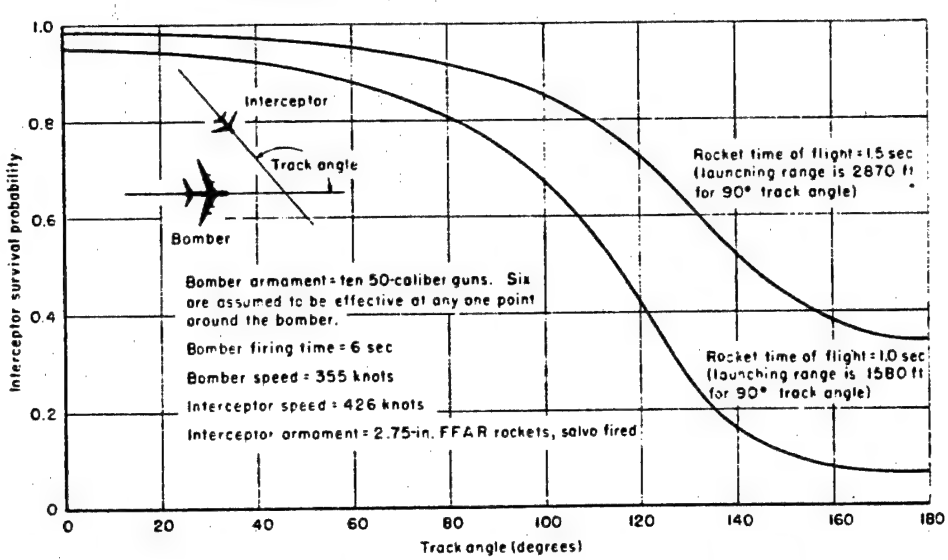


Fig. 19—Effect of all-around bomber armament on interceptor survival probabilities

killed would have a fair chance of launching their ammunition before being hit. Hence, it was felt that forward-hemisphere armament would be relatively ineffective in protecting the bomber. Since armament is detrimental to range,

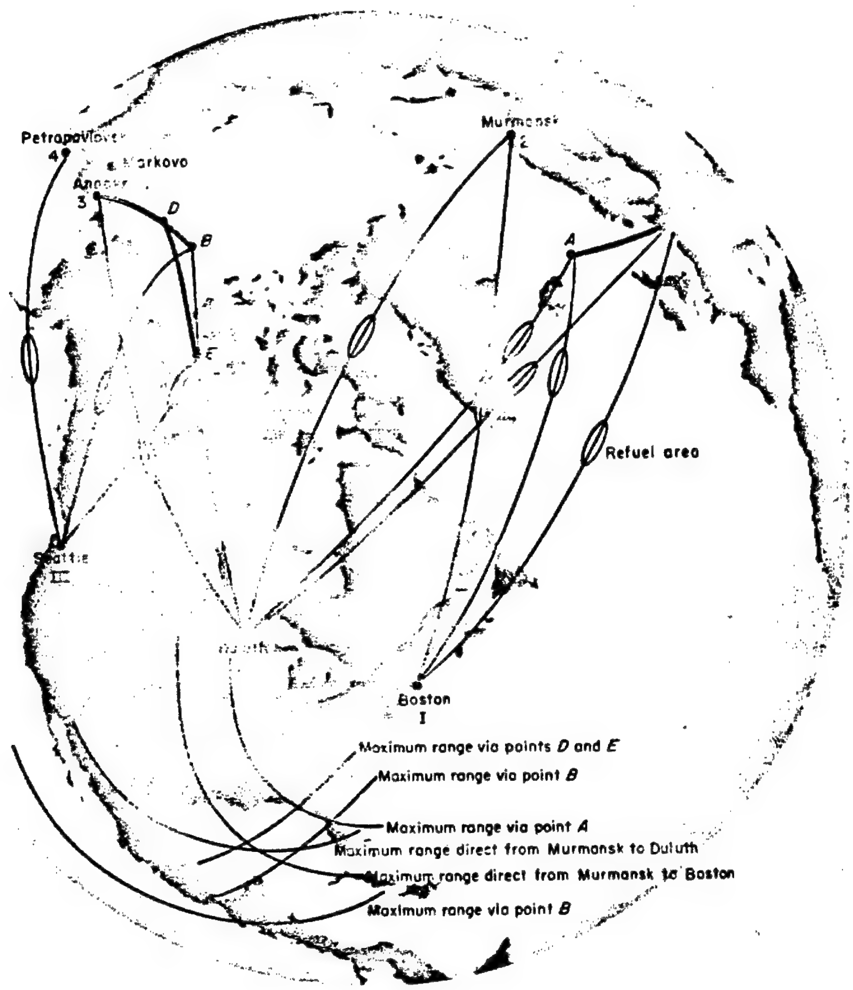
and since the bombers hypothesized generally need all the range capability they can get, it was assumed that only twin 30-mm tail turret guns would be carried by all bombers. The angular coverage of this turret was assumed to increase in the more advanced bombers. The values are $\pm 70°$ for the TU-4, $\pm 90°$ for the Stalin and the Volga, and $\pm 110°$ for the Lenin.

The interceptor radar must lock on the bomber some seconds before firing. This helps the bomber to lock on the fighter because of the large echo area of the fighter's radar antenna when it is pointed at the bomber. Or, possibly, the enemy will be able to build automatic gun-laying equipment utilizing the energy from the fighter's radar, the characteristics of which he will probably know. Therefore, it is assumed that the bomber's guns are always effective against a fighter within their coverage.

It was estimated that bomber-launched air-to-air guided missiles would not be operational on Soviet LRAF bombers before 1958. This is nearly the end of the time period of the study, so such missiles were not considered in detail. By 1958 it is hoped that a sizeable share of the defense burden will be carried by surface-to-air missiles. When bomber-launched missiles appear, the effectiveness of the interceptors will be reduced, particularly those armed with guns or rockets. Hence, long-range air-to-air missiles would become the preferred interceptor armament.

IV. Aircraft Attack Patterns

Various possible attack patterns are feasible, depending on winds, territories hostile to Soviet bombers, the geography of the United States target system, etc.[7] In the case of the one-way unrefueled TU-4 and the once-refueled round-trip Stalin bomber, the distances are such that attacks on all of our important targets are possible from USSR-controlled bases, with considerable leeway for by-passing Alaska, Scotland, and Iceland. The geography is such that overwater approaches to both coasts are possible and bombers could come in the direction which would minimize early warning. Targets in the central area of the country could be attacked from bases on the Chukotski Peninsula or from bases near Murmansk. Some of these possible routes and distances are shown on the maps of Figs. 20 and 21.



Six of the most probable attack routes

To	Route	Distance (n mi)	Percentage of increase because of weather	Increased distance (n mi)	Remaining range (n mi)
Boston	1-A-I	3500	20	4200	1000
	2-I	3400	15	3900	1300
Duluth	2-II	3500	12	3900	1300
	3-B-II	3100	10	3400	1800
Seattle	3-B-III	2700	12	3000	2200
	3-D-E-III	2900	12	3200	2000

Fig. 20—Possible attack routes for one-way once-refueled TU-4 bombers

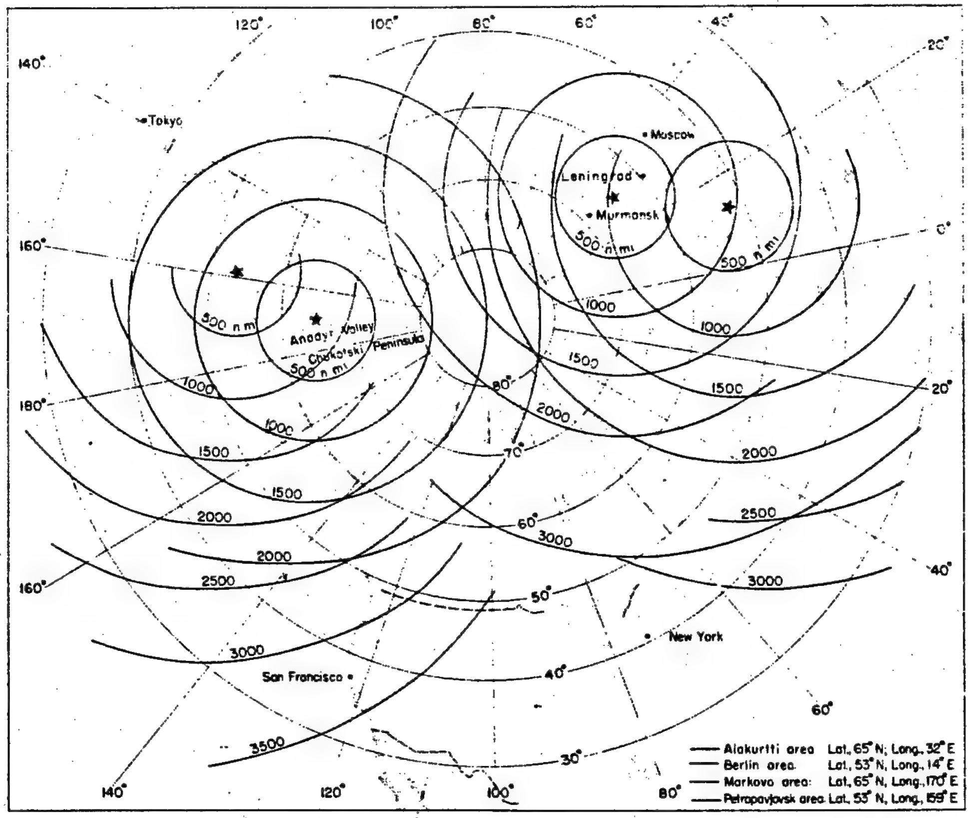


Fig. 21—Great circle distances from four possible Russian bases

The Volga bomber has a radius in excess of the capabilities of the TU-4 and Stalin bombers mentioned above and hence would provide even greater flexibility in choice of routes.

The Lenin bomber does not have an intercontinental capability. To attack targets in the United States it would either have to be carried by a very large mother airplane, start from an advance base such as Alaska, Northern Canada, or Mexico, or be refueled at least twice. Hence, no routes were studied for this aircraft.

In part of the study it was considered that one bomb would be dispatched per aiming point chosen by the LRAF and that the bomb carrier would be accompanied by several other aircraft acting as escorts and carrying electronic-countermeasure equipment or reconnaissance equipment. In other cases, particularly when a large bomb stockpile and strong defense weapons were con-

sidered, the dispatch of several bombs to one aiming point on one strike was investigated.

For some calculations it was assumed that the enemy aircraft would approach in a wave formation, trying to penetrate the radar screen at approximately the same time to put the maximum burden on our capacity to handle our interceptors. In this case it was determined that, in general, the interceptors would not have time after attacking a bomber to return to base, land, refuel, rearm, and return to combat before the bomber wave had passed over. After entering the interceptor defenses, the bombers would fly in small cells toward each area to be attacked. A quite different strategy studied assumed that bombers might come over in one or a few streams, each stream flying over several targets in succession. Any particular bomber would thus pass over several locally defended areas, exposing itself to defense fire each time. However, because of the resulting larger number of bombers over each local-defense area, the defense firepower was considerably diluted. It turned out that this tactic was not greatly different from others in its effectiveness and, since it was much more difficult for the bomber force to accomplish, it was not considered further.

The Soviet LRAF could strike with any of several degrees of intensity, continuing until the whole bomb stockpile committed to attack on the ZI was used up. This could be visualized in several ways:

One extreme would be a single massed strike delivering the whole stockpile of bombs with the whole stockpile of available aircraft. Such an attack would take maximum advantage of the effects of both surprise—in the sense that the defense could learn from the first strike how to react to later strikes—and saturation, and would attempt to overpower our defenses. In this type of attack the choice left to the attacker is the number of aiming points to which he will dispatch his bombs and hence the number of bombs per aiming point. It would be assumed that the attacker would make this choice with knowledge of the defense properties and would seek to maximize the physical destruction of the United States target system. A consideration of Russian military doctrine and general code of behavior indicates that this is a very likely form of attack. It is felt that the Russians would favor a crushing blow, calculated to destroy our physical capability to resist, rather than the use of such psychological effects as suspense or panic which might attend an extended campaign.

Another pattern would be to deliver the bomb stockpile in several moderately heavy strikes. Using this strike pattern, it would be possible for the offense to do somewhat more total damage against certain types of defense systems (if the strikes were properly proportioned and if there was no "learn-

ing" of offense or defense) than with the single mass strike. This maximum damage could be achieved in three or four strikes in a typical case. If this pattern were used, the later strikes might be better planned if results of the earlier strikes were known; but if these were one-way raids, there would be no advantage arising from crew combat experience.

A third pattern would be to launch a number of attacks by single aircraft or by very small bombing cells. Such attacks would hope to sneak through our defenses.

If we knew which of these types of attack would be used, it would have some effect on our defense-weapon choice. The last type of attack is one where the burden of the defense would rest on the effectiveness of our radar network and identification procedures. Most of the defense weapons of the RAND study would be effective against such an attack if the radar network is efficient or spotters do their job well. Conversely, a single strike would give the radar network the best chance of detecting and identifying the enemy aircraft but would place the burden on weapon and control-system effectiveness.

It would have been possible to consider which type of attack the enemy would be most likely to launch, taking into account his military objectives and past doctrine. This was done only tentatively in the present study and consideration of all three types of attack was retained. As far as weapon choice is concerned, however, the single strike seems to be the most important case. Even if there were a few "feeler raids" at the outset, to test our reaction and the operational readiness of the offense, the decisive phase of the air war could still be a massive strike, essentially like the single strike. The sequence of events, and the condition of alert, would undoubtedly be influenced by political and diplomatic events of the time. Some steps can be taken to minimize the value of a surprise move by the enemy. A preliminary investigation of surprise and learning was made in connection with the RAND defense study; it resulted in the suggestion of several ways of minimizing the effects of surprise.[*]

RAND's defense study considered both high- and low-altitude attacks, as well as both day and night (or bad visibility) attacks for one-way and round-trip missions. These different attack tactics resulted in different defense performances.

V. Operational Performance: Bombers

To calculate the expected damage to our target system it is necessary to estimate Soviet bombing accuracy. It was found that for *city bombing* the effect of CEP[9] would be so small that the damage to residential sections would be essentially the same as when there was no aiming error. (A trial exploration was made on this point.) For an *industry attack,* the values estimated were:

	CEP (ft)
High altitude, poor visibility or night	4800
Low altitude, poor visibility or night	3600
High altitude, daytime (good visibility)	3000
Low altitude, daytime (good visibility)	2500

These values assumed that *radar* bombing would be done under conditions of poor visibility and that *optical* bombing would take place when visibility was good. A much more elaborate treatment would have assumed different CEP's for different classes of radar targets or different training levels of various crews, etc. However, this refinement was not felt to be justified in the present study because the analysis sought recommendations for preferred defense weapons, not preferred offense techniques or weapons.

In addition, it is known that some bomber crews make gross errors and miss the target entirely. The estimated percentages for these errors were:

City bombing, night attack	5%
City bombing, day attack	5%
Industry bombing, night attack	20%
Industry bombing, day attack	10%

It was assumed that for the first strike the Soviet Union would take the initiative and could, therefore, have 90 per cent of their aircraft available for combat missions. On subsequent strikes, an availability figure of two-thirds was assumed. Operational losses, i.e., noncombat losses on the way to United States targets, were estimated to be 5 per cent in high-altitude attacks and 10 per cent in low-altitude attacks. Aborts were taken to be an additional 5 per cent for both (with aborting airplanes returning to base).

It is necessary to assume something about the formation design and spacing of enemy bombers in planning both interceptor defenses and local defenses and

[9] Circular error probable (CEP) is the radius around the aiming point which is expected to contain half the ground-zero points.

in measuring their effectiveness. Nothing applicable is known about Soviet doctrine, either from intelligence sources or from World War II data, so a range of possible tactics has been considered. For example, the most effective penetration of the high-altitude local-defense weapons would be achieved by flying in formations where the spacings were of the order of several thousand feet, thereby causing maximum trouble for surface-to-air missiles trying to resolve multiple targets. For low altitudes, the aircraft should have very close spacings over the light guns which provide the low-altitude local defense in the present study. On the other hand, against interceptors, it might be preferable to fly with very open spacing (10 miles or more) to make the ground-control job as difficult as possible and to minimize the chance of an interceptor's being able to attack several bombers in one sortie. Several of these possible tactics have been examined in studying the relative effectiveness of various defense weapons.

VI. Low-Altitude Attack

One of the important aspects of the present study concerns defense against *low-altitude atomic bomb attack.* Such an attack, which is shown to be extremely profitable for the offense, raises the question of effective delivery of the A-bomb at such altitudes. It is felt beyond question that this is feasible for the Soviet Union for several reasons. First, they may very well have committed their bombers (at least the TU-4's) to one-way attacks on our targets. This means that they would be willing to employ a bombing tactic which would result in loss of their aircraft. Further, they have such great knowledge of the terrain characteristics of this country that low-altitude navigation need not be a difficult problem. In addition, it is possible that they could have radio or radar beacons planted by their agents to guide them to the target.

The bomb might be delivered at the proper altitude for an air burst by at least the following methods:

1. They could approach the target at 500 to 2000 ft (depending on visibility). The crew could bail out just before entering the local-defense area and the aircraft could proceed on autopilot, dropping the bomb automatically. Or, by use of a programmed maneuver, the aircraft could zoom up to optimum burst height immediately before the bomb explosion. This could be done quickly enough to avoid effective fire from the higher-altitude weapons. An alternative method would be a

combined zoom and climb to about 3000 ft at the last minute, the bomb being dropped on a ribbon parachute so that it would go off when the aircraft was a reasonably safe distance away.

2. A different delivery method might make use of a crude guided bomb or air-to-surface missile to get the bomb to the optimum altitude far enough away from the carrier so that the bomber would not be damaged or subjected to the full weight of the local defenses. This seems reasonable in the light of the progress of some of our own development programs. Although the accuracy of such an attack might be less than that of more conventional bombing, it should still be satisfactory for attacks on big cities. It is felt that all of these or similar tactics could be employed efficiently by the Soviet Union.

VII. Offense Missile Characteristics

Although there is no direct supporting intelligence evidence, enemy aircraft were assumed to have the capability of carrying air-to-surface missiles throughout the period of the study. It was assumed that the air-to-surface missiles in the period up to about 1957 would be quite simple subsonic (450-knot speed) missiles of such short range (compared with the interceptors) that interceptor kills could be made on an aircraft before release of a missile. It was assumed that in the 1957 period the missiles would be supersonic (2000-knot speed), so that the interceptors would have no defense capability, and that the missiles would be of such long range that by proper enemy tactics even long-range defense missiles would have to be delivered against both the mother aircraft and the air-to-surface missiles. (See Fig. 18, page 86.)

A detailed specification of the air-to-surface missile was not felt to be necessary for the purposes of this study. However, for the purposes of assessing vulnerability and making radar detection studies, it was assumed that the early air-to-surface missiles would be rocket powered and of a size similar to that of the Rascal missile.

Intelligence reports on enemy test firings indicate the possibility of the use of V-1–type missiles, with atomic warheads, delivered against coastal targets from submarines. For the purpose of vulnerability calculations it was assumed that the missiles would be identical with the V-1's of World War II.

There is intelligence information indicating enemy development of long-range intercontinental glide rockets or ballistic rockets. It was assumed that

their rocket capability would be realized toward the end of the period of study (1960). However, the study of the defensive-missile system to counter this threat is not at present completed, so that the long-range rocket threat was not further treated in this study. Similarly, there may exist a threat of submarine-launched supersonic rockets similar to the V-2. This threat may be met by a system employing the Bomarc concept or by the advanced local-defense missiles discussed later. In addition, there is the possibility of action against the submarine itself. These matters are not discussed in detail in this report.

In making some of the numerical calculations it was assumed that the number of air-to-surface missiles used in the attack would be the same as the number of aircraft; i.e., each aircraft capable of carrying a missile would do so.

VIII. Operational Performance: Air-to-Surface Missiles

The expected bombing error resulting from the employment of air-to-surface missiles by the Soviet Union depends critically on the development of missile-guidance equipment. Essentially nothing is definitely known about their capabilities in this regard. It is felt that against city targets they should be given the capability of guidance to an accuracy of 10,000 ft CEP for short-range air-to-surface missiles in the early periods of the defense study and for medium-range missiles in the later periods of the study. One guidance technique which might be employed is homing on beacons planted by enemy agents. By this means very high accuracies could be achieved.

Gross errors, availability, aborts, and operational losses in the case of air-launched missiles are assumed to be the same as for the bombers alone, plus an additional 25 per cent for missile malfunction at or after launching.

Although the range of a supersonic missile is considerably reduced by flight at low altitudes, it was estimated that some capability for a low-altitude air-to-surface missile attack would be attained by the Soviets even though the high-altitude range of the missile itself was as low as 20 miles.

IX. Offense Weapon Characteristics

that would be available to the USSR in 1953. It was estimated that at that date 100 could be committed against the ZI, allowance being made for a part of the stockpile to be allotted to England and Western Europe or to be held in reserve. It was assumed that in later years the stockpile committed to attacks on the ZI would increase to several hundred bombs. The exact numbers used in the study might not represent the best use of Russian fissile material; instead, more might be diverted to tactical use or be made into larger weapons. However, the study postulated quite a large number for the period of 1957–1959 to allow for repeated attempts to penetrate our defenses or for the dispatch of several bombs per aiming point. At this stockpile level the offense would no longer be bomb-limited but bomber-limited. It is felt that the inclusion of a smaller number of much more powerful bombs would not have made any major change in the results of the study.

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CHAPTER 6

INTERCEPTOR PERFORMANCE AND COST

For use in the Air Defense Study, two generations of interceptors were examined in detail. The first generation, consisting of presently planned equipments, may be considered applicable during the years 1953 to 1958. A second generation, which could result from immediate initiation of a development program, might be considered for use after 1957. The availability dates and the life-span of these interceptors and their armaments are shown in Fig. 22.

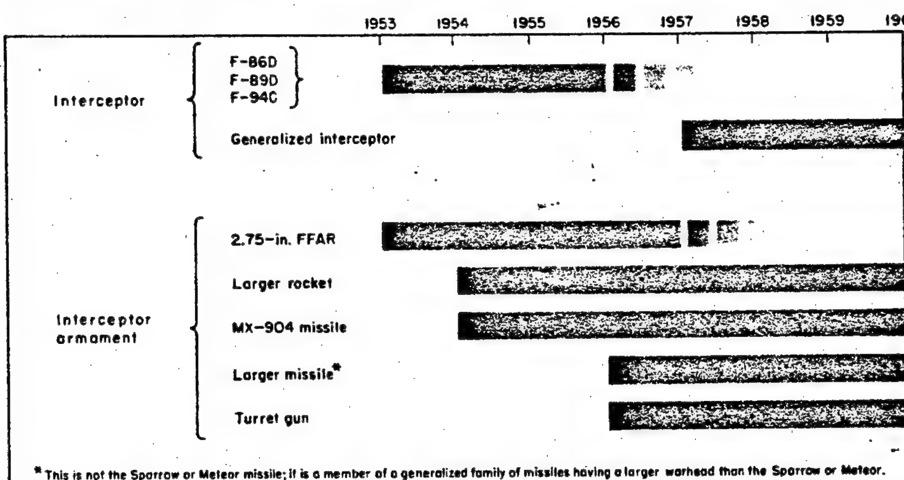

Fig. 22—Availability dates of interceptors and interceptor armaments

I. First-Generation Airplane Performance

The primary airplanes available for defense in this time period are those of the present Air Force program, the F-86D, F-94C, and F-89D; in addition, a B-45C modification could be available. These aircraft were considered for use against the TU-4's only and their performance characteristics were determined by using manufacturers' basic data for two extreme conditions: a "long-range" operation and a "frantic" operation. Wing-tip fuel tanks were carried in both

cases, since they improve the radius characteristics materially at a small sacrifice in performance. For each of these operations, combat radius was determined as a function of target altitude and combat time.

The radius rules of the long-range and frantic missions were set up in a specific manner for the calculations.[1] For the long-range mission, the F-86D, F-89D, and F-94C each have a combat radius of roughly 300 miles with combat times of the order of 10 minutes. The B-45C interceptor modification would have a combat radius of the order of 800 miles. The F-86D, F-89D, and F-94C all have enough maneuverability and speed at altitude to combat the TU-4 bomber effectively and all have satisfactory times-to-climb to the combat ceiling of the TU-4. The B-45C interceptor modification would be a lower-performance aircraft having longer time-to-climb. This aircraft, if used, would require ample radar-warning time, since its distance in climb to 35,000 ft is of the order of 160 nautical miles.

Lacking more definite information, it was assumed that in the time period of these airplanes the air defense force would have 61 squadrons consisting of 36 squadrons of the F-86D, 10 squadrons of the F-89D, and 15 squadrons of the F-94C. The B-45C was considered as an alternative aircraft in small numbers.

[1] The exact rules used are summarized below.

1. "Long-Range Mission":

Take off with maximum thrust. With military thrust, accelerate to best climb speed and climb to the optimum nonafterburning cruise altitude. Fly out, without afterburning, at maximum-range conditions. Descend to target altitude (no distance credit) or climb to target altitude with the maximum thrust. Expend ammunition during combat (the combat time is varied, thereby resulting in varying radii). The flight speeds associated with combat are either the speed for maximum-range flight without afterburning or a speed roughly 20 per cent greater than that of the target speed at each appropriate target altitude, whichever is higher. Climb at military power to optimum cruise altitude or descend (no distance credit) and return to starting point at maximum-range conditions. Fuel reserves are sufficient for 15 minutes' loiter over home base at optimum return altitude at maximum endurance speed and for 5 minutes' loiter at sea level at maximum endurance speed. A 5 per cent safety increase in the engine manufacturers' fuel-consumption estimate is used.

2. "Frantic Mission":

Climb at maximum thrust to the altitude of the target. Proceed out at maximum thrust at this altitude. Expend ammunition during combat. The flight speeds for combat, the return to base, and the fuel reserves are the same as those for the long-range mission.

II. First-Generation Airplane Costs

Costs of first-generation interceptors were determined for 61 squadrons and 50 bases. Each squadron consisted of 25 assigned mission aircraft plus an additional 10 per cent command support aircraft. The costs of this force were programmed over the years, as described in detail in RM-662.[2] For the purpose of defense-weapon comparison, however, a single measure of cost was used. This measure is called "total annual cost" and consists of the annual operating cost plus one-fourth of the initial cost. This implies a 4-year life for the equipment. All costs are given in 1950 dollars.

The initial cost of the mission aircraft, organizational equipment, expansion of installations, etc., for this force would be $1,536 million. The cost of mission aircraft for these organizations would amount to $487 million for the F-86D, $269 million for the F-89D, and $151 million for the F-94C. Mission-aircraft costs represent from 48 per cent to 69 per cent of the total cost of activating the squadrons. Seven squadrons would be available at the end of Fiscal Year 1951; another 25 would be added during 1952; 21 would enter service in 1953; and the remaining 8 would be activated in 1954.

The next major items of expenditure are for personnel and the expansion of installations. These account for approximately 11 per cent and 17 per cent, respectively, of the total initial cost. The major items for each type of airplane and the number of squadrons to be activated for the total of 61 squadrons are shown in Table 3.

The 23 squadrons equipped with types of aircraft in operation on July 1, 1950, were assumed to be available without cost to the new program. Accordingly, only the additional equipment and supplies required and the recruitment and training of additional personnel were treated as initial costs.

Similarly, since some of the bases in existence on July 1, 1950, would be utilized in the new program, the cost of these installations was treated in terms of expansion of bases required by the new type of equipment and the rehabilitation of inactive bases, or in terms of the building of new bases necessitated by the expanded program. Figure 23 (page 108) shows the bases now in use for air defense and other bases which might be used in the near future. (Present USAF plans do not agree exactly with Fig. 23, which shows the bases considered in the study.)

Table 3

COST OF FIRST-GENERATION INTERCEPTOR FORCE

(Millions of Dollars)

1952–1956 Interceptor Plan: Costs of equipping, manning, installing, and operating a force of 61 squadrons. Build-up starts July 1, 1950. June 30, 1954, force: 36 squadrons, F-86D; 15 squadrons, F-94C; and 10 squadrons, F-89D. Initial cost includes new equipment, training of additional personnel, expansion of installations, etc., from the 23 squadrons of previous-type fighter-interceptors in operation on July 1, 1950. Annual cost is replacement of equipment and men, operations, etc.

Cost Item	36 Squadrons (F-86D)		10 Squadrons (F-89D)		15 Squadrons (F-94C)		61 Squadrons	
	Initial	Annual	Initial	Annual	Initial	Annual	Total Initial	Total Annual
Installation:								
Equipment facilities	96	...	32	...	40	...	168	...
Personnel facilities	48	...	18	...	24	...	90	...
Maintenance	...	9	...	3	...	4	....	16
Major equipment:								
Mission aircraft	487	71	269	31	151	24	907	126
Unit support aircraft	7	(*)	2	(*)	3	(*)	12	1
Minor equipment:								
Organizational equipment	61	5	23	2	33	3	117	10
Ground radar	18	...	5	...	8	...	31	...
Initial stock level	15	...	6	...	5	...	26	...
Transportation	5	...	2	...	2	...	9	...
Personnel:								
Training	88	30	33	10	48	15	169	55
Pay and allowances	...	144	...	52	...	79	....	275
Travel	4	3	2	1	3	2	9	6

* Less than $0.5 million.

Cost Item	36 Squadrons (F-86D)		10 Squadrons (F-89D)		15 Squadrons (F-94C)		61 Squadrons	
	Initial	Annual	Initial	Annual	Initial	Annual	Total Initial	Total Annual
Maintenance:								
Mission aircraft	...	40	...	18	...	14	....	72
Support aircraft	....	14	...	6	...	8	....	28
POL:								
Mission aircraft	...	14	...	10	...	9	....	33
Support aircraft	...	5	...	2	...	3	....	10
Service and miscellaneous†	...	18	...	6	...	9	....	33
Intermediate commands‡	...	23	...	8	...	12	....	43
Overhead**	...	118	...	47	...	57	....	222
TOTAL	829	494	391	197	316	239	1536	930

† *Service and miscellaneous:* The estimate for "service and miscellaneous" costs covers all annual operating and maintenance costs for the wing other than those specifically itemized above. It includes such costs as temporary-duty travel, contractual transportation, and supplies for administration, flight service, and welfare.

‡ *Intermediate commands:* "Intermediate commands" is the estimate of the proportionate share per wing of expenses of all Air Defense Command echelons above the wing level.

***Overhead:* As used in this analysis, "overhead" is the proportionate share per wing of all Air Force costs other than those of tactical operating commands and their directly costed support. With the exception of those costs of the Air Materiel Command and the Air Training Command, which have been costed directly as depot maintenance and personnel training, "overhead" includes a proportionate share of operating costs of all nontactical commands and of HqUSAF.

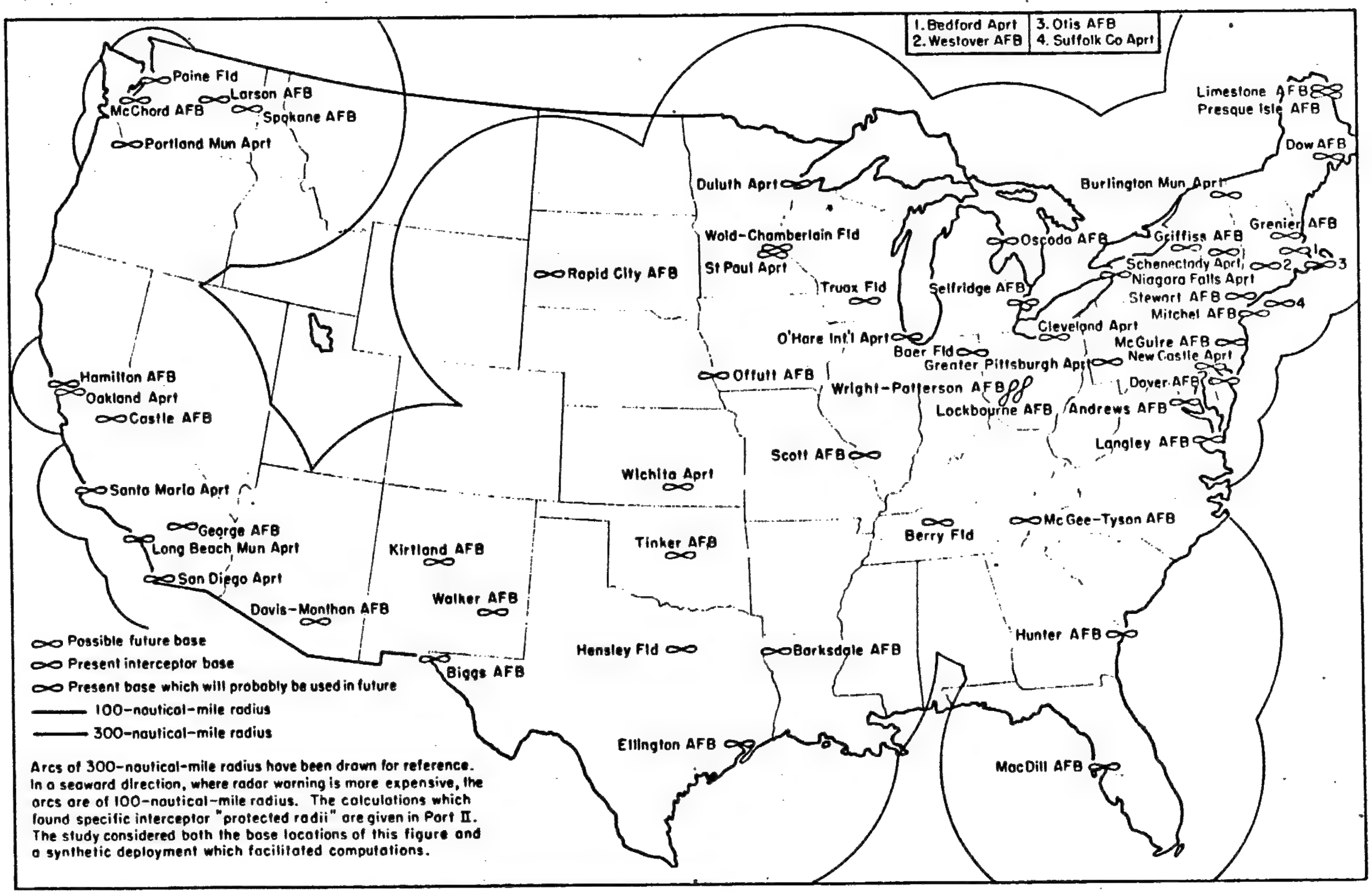

Fig. 23—Present and possible future bases for air defense interceptor operations

Annual costs were calculated for estimated peacetime attrition rates for mission aircraft of 15.7 per cent and for a 25 per cent per annum turnover in personnel in the ZI. The "total annual cost" of maintaining and operating this force of 61 squadrons would be $930 million. Approximately $330 million of this would be for personnel; about $126 million, for the replacement of mission aircraft; and $265 million, for overhead. Most of the remainder would be required for supplies and maintenance.

III. Second-Generation Airplane Performance

This time period is far enough in the future that the expected characteristics of interceptors for use in this period had not been definitely fixed when the defense study began. This left open such an extremely wide range of possible characteristics that a generalized interceptor study[3] was made exhibiting the allowable relationships between these many interceptor characteristics.

The interceptor study describes the technical design capabilities of interceptor aircraft and not the detailed airplane design. The purpose of the study was to:

- Determine interceptor characteristics as a function of the design variables.
- Permit comparison of armaments and tactics by making different demands on the interceptor in regard to payload, maneuverability, etc.
- Carry the weapon potentialities of the interceptor as far into the future as possible to permit a comparison with other types of weapons, such as guided missiles.

The interceptor study presents quantitative relationships between initial gross weight, combat speed, combat altitude, combat maneuverability, armament type and amount, combat radius, and combat time for transonic and low-supersonic-speed interceptor aircraft whose design and operation have been optimized to yield greatest range. Only unrefueled operations, without wing-tip tanks or other external stores, of single-place all-weather turbojet-plus-afterburning[4] aircraft are considered.

A sufficient number of assumptions were made and design composition rules devised to express generalized characteristics of the airplane. The results represent the best possible performance that can be obtained within the limits defined by the assumptions of the study.

An adequate number of the airplanes of this study were evaluated against the various assumed enemy threats to provide an approximate "preferred" interceptor for each of the threats considered. Some illustrative results showing general trends of the interceptor study are presented in Figs. 24 through 30.

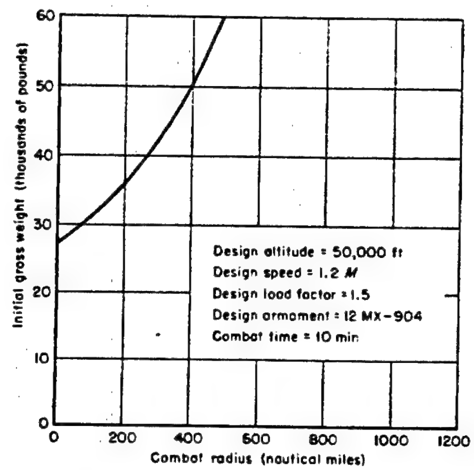

Fig. 24—Initial gross weight vs combat radius

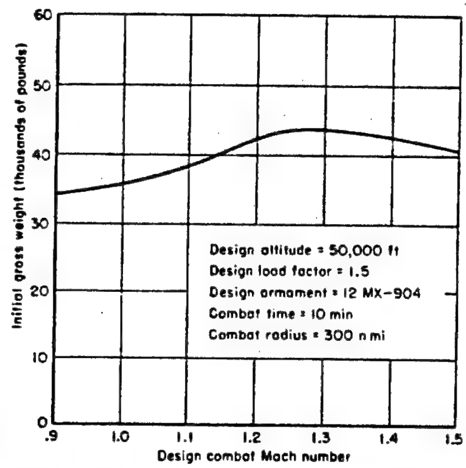

Fig. 25—Initial gross weight vs design combat Mach number

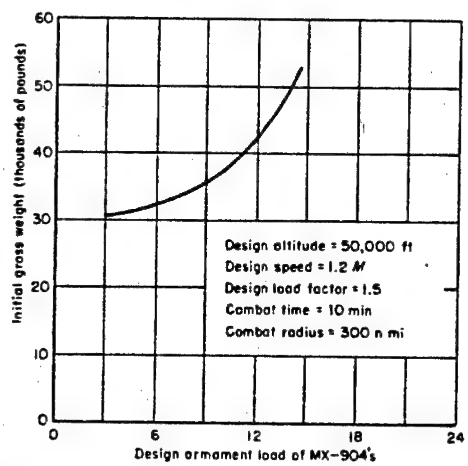

Fig. 26—Initial gross weight vs design armament load

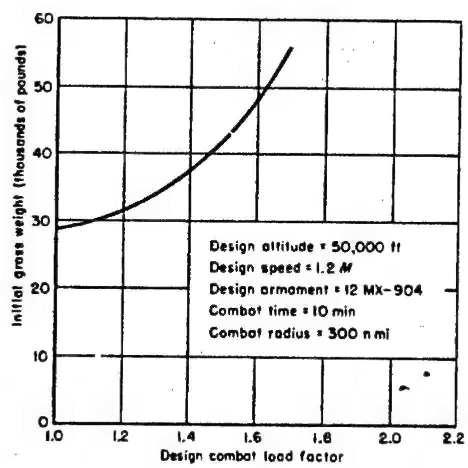

Fig. 27—Initial gross weight vs design combat load factor

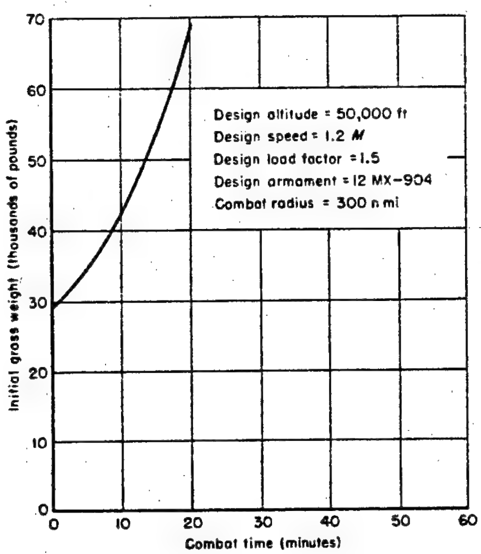

Fig. 28—Initial gross weight vs combat time

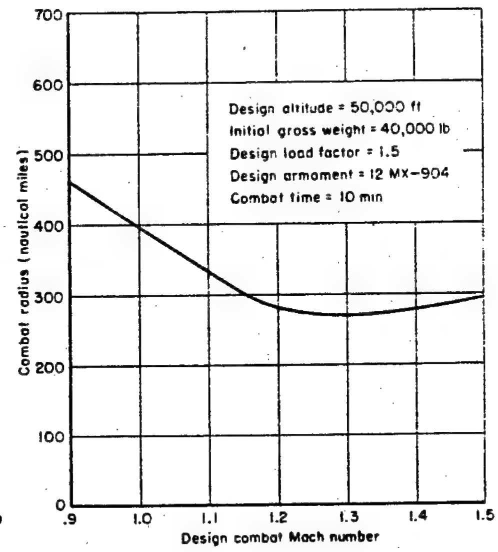

Fig. 29—Combat radius vs design combat Mach number

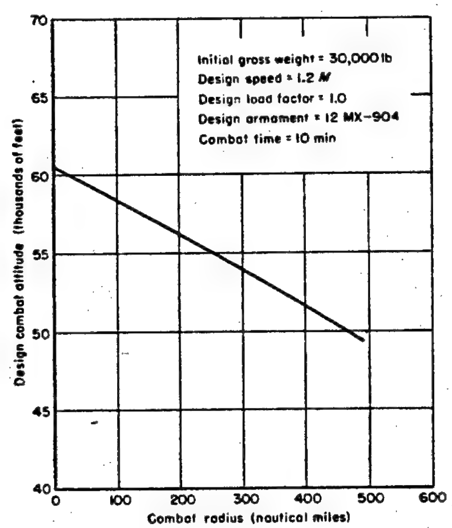

Fig. 30—Design combat altitude vs combat radius

IV. Second-Generation Airplane Costs

It is understood that a new interceptor, the MX-1554, is to be programmed to become available in operational quantities beginning in July, 1956, and ending in July, 1958. Again, for purposes of estimating costs, an arbitrary figure of 61 squadrons was assumed. However, in the Defense Systems Analysis (the numerical part of the study) it was assumed that the cost of this re-equipping program would be proportional to the number of aircraft procured. The costs of this new interceptor are those incident to the changeover in equipment between July, 1956, and June, 1958, and for operations conducted solely with this equipment in the period beginning July, 1958, and ending in June, 1960.[5]

The major components of the cost of introducing the new interceptor are those for the initial equipment and its maintenance and operation. There will be an added manning and training requirement arising from the use of more highly developed electronic equipment and because the new interceptor will be equipped to fire air-to-air guided missiles. The addition of specialized personnel, missiles, and more complicated electronic equipment will also require some additional organizational and maintenance equipment and will necessitate an augmentation of stock level.

Since the new interceptor replaces old equipment, it was assumed that the costs of all organizations in place, all available installations, all support aircraft, and related installations, equipment, and men available from the existing force would not be chargeable to the new interceptor.

No salvage value is given to the 61 squadrons which will remain on hand at the end of the operational-life period in July, 1960. The annual charges were defined to be the total costs, including peacetime attrition of equipment, turnover of personnel, maintenance and operation of equipment, men, installations, and the organizations required at the higher levels of the Air Force.

Figure 31 (on page 114) shows the cost data for missile-armed interceptors. For rocket-armed interceptors the initial and annual costs per squadron are reduced by approximately $2 million and $3 million, respectively. Itemized costs for a missile-armed interceptor of 15,000-lb weight empty are shown in Table 4.

[5] It was realized that evolutionary improvements will be made to first-generation interceptors in the interim before the second generation becomes available.

Table 4

TYPICAL COSTS OF SECOND-GENERATION INTERCEPTOR FORCE

(Millions of Dollars)

Interceptor Weight Empty = 15,000 lb

Costs of equipping, manning, installing, and operating a force of 61 squadrons. Phasing-in begins on July 1, 1956, and is completed on June 30, 1958. Operation continues through June 30, 1960. Initial cost includes new equipment, training of additional personnel, expansion of installations, etc. Annual cost includes replacement of men and equipment, operations, etc.

Cost Item	Initial Cost for 61 Squadrons	Annual Cost for 61 Squadrons
Installation:		
Equipment facilities	8	...
Personnel facilities	13	...
Maintenance	...	24
Major equipment:		
Mission aircraft	768	110
Support aircraft	...	1
Minor equipment:		
Organizational equipment	14	10
Ground radar	...	6
Initial stock level	8	...
Transportation	1	...
Personnel:		
Training	21	59
Pay and allowances	...	294
Travel	1	7
Maintenance:		
Mission aircraft	...	77
Support aircraft	...	20
POL:		
Mission aircraft	...	32
Support aircraft	...	7
Service and miscellaneous†	...	36
Intermediate Commands‡	...	45
Overhead**	...	228
TOTAL	834	957

For footnotes, see Table 3, page 107.

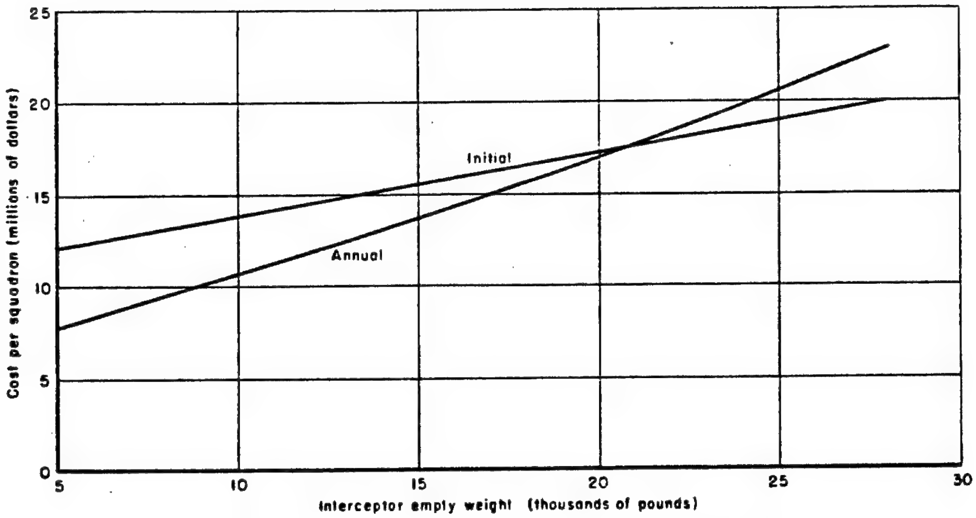

Fig. 31—Estimated costs of missile-armed interceptors

V. General Discussion

Consideration of the air battle aspects of the air defense problem, particularly the probability of AI radar detection and conversion, and of interceptor load economy (one pass versus multiple passes, each pass having high lethality) indicates that an optimum combat time is of the order of 10 minutes. This time is sufficiently great that, for a single type of interceptor force, the turbojet is felt to be the best powerplant type, or very close to the best.[6] Hence, other powerplant types were not considered in any detail. Obviously there will be specific applications (e.g., for defense of certain highly valuable targets or targets with little radar early warning) where the rocket or ramjet types would be preferred or would be used to give a measure of extra safety.

Only conventional interceptor aircraft were considered in the qualitative work. The use of droppable landing gear, short take-off launchers, the British landing-mat technique, etc., might result in some saving if found to be operationally feasible.

The long-range-mission type was used wherever there was adequate warning time available, since this results in a considerably greater combat time and only a slight sacrifice in average speed. It should be mentioned here that the early

[6] Actually, the ducted fan is superior for certain applications but was considered not to be sufficiently developed for the time period of this study.

warning time available was one of the parameters of RAND's Air Defense Study. Thus, cases were considered in which all the interceptors were utilized in the long-range type of mission (complete ZI coverage and large coverage outside the ZI) and also cases in which a large fraction of the fighters were used in the frantic type of mission (small radar early warning).

It had been hoped that the RAND interceptor study[7] would be completed prior to the selection of interceptors to combat each of the various enemy threats. However, the selection had to be made from the cases which were available. Interceptors to combat the Stalin-type bomber were drawn from combat altitude of 50,000 ft and combat speed of Mach 1.0 to 1.4. Illustrative examples are given in Fig. 32. To combat the Lenin-type bomber, interceptors were drawn from aircraft having combat altitudes of 50,000 ft, 55,000 ft, and 60,000 ft and a combat speed of Mach 1.2. Examples for this case are given in Fig. 33. For both of these bomber threats, various combat load factors, combat radii, combat times, and armament types and amounts were investigated, thus defining interceptors of various gross weights.

A particular interceptor can be flown over a wide range of speeds and load factors, depending on the flight altitude and the rate of change of altitude.[8] The interceptors considered in the defense study were investigated and evaluated for various types of attacks, which included the trading of speed for transient maneuverability and the use of the interceptor at average conditions that differed from the design conditions.

A peculiarity of the turbojet-plus-afterburner type (as studied in RM-561[9]) is that when it is designed for a supersonic combat speed well above the transonic drag rise, the actual top speed is limited only by structural, heating, or fuel-flow problems. This anomaly results because the powerplant thrust rises more rapidly than does the drag as the speed exceeds the design value. Consequently, if sufficient time is available for acceleration up to speed, a broad speed–load-factor region is usable by these aircraft.

This region is illustrated in Fig. 34 for the interceptor family having a design combat speed of Mach 1.2 at 50,000 ft altitude and a sustained load-factor capability of 1.25. As this figure shows, the maximum speed in this case is bounded by the engine structural limitation at Mach 1.94. The maximum load factor is limited by the maximum lift coefficient obtainable at the given speed.

[7] See footnote 3, page 109.

[8] The discussion given here is restricted to the case where the rate of change of altitude is zero. Attacks for which this is not the case are discussed in Chap. 7, "Air Battle Analysis."

[9] See footnote 3, page 109.

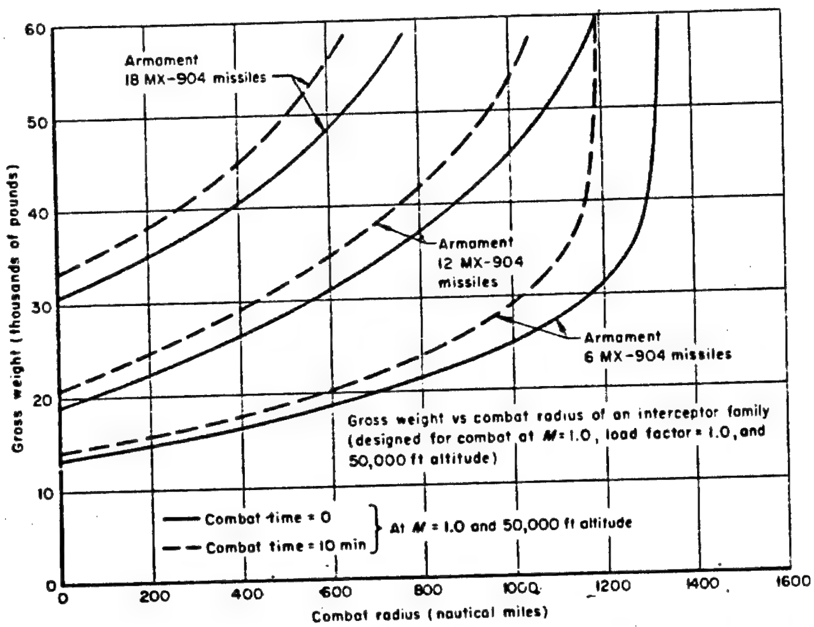

Fig. 32—Characteristics of interceptors designed to combat the Stalin-type bomber

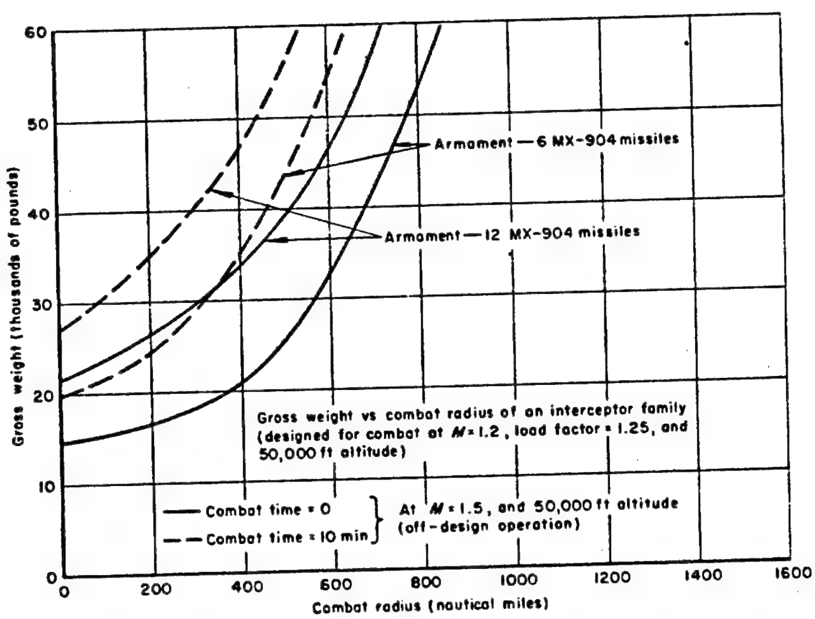

Fig. 33—Characteristics of interceptors designed to combat the Lenin-type bomber

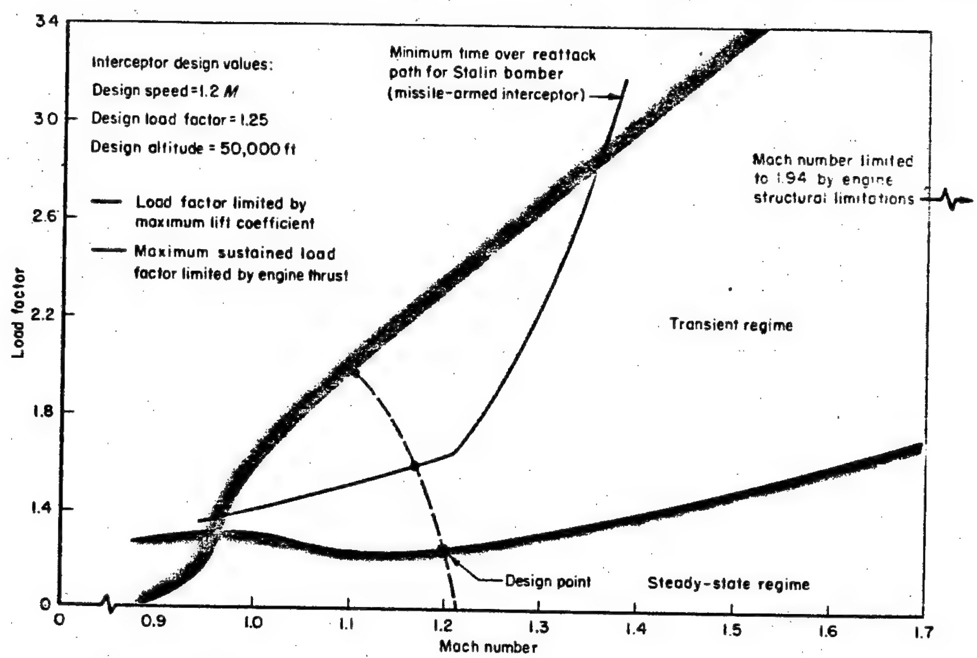

Fig. 34—Available combat operating region at 50,000 ft altitude for a typical interceptor

This maximum load factor, in general, cannot be sustained without loss of speed. The maximum load factor which can be maintained with full thrust available and without loss of speed is shown as the boundary between the transient and steady-state operating regime. This line passes through the combat design point.

The dashed line shown through the design point serves to define the average-speed and load-factor combinations obtained over a specified reattack path,[10] when the path is initiated at the lock-on point at design combat speed and is thereafter flown at maximum thrust. The method used to synthesize the deceleration in the turns and the acceleration in the straight portions of the reattack path in order to produce a successful reattack is given in detail in RM-575.[11] This same line also separates the operating region into two parts: to the left of this line, the combat radius, as determined by the rules of the generalized interceptor study, is valid; to the right of this line, the combat radius must be re-

[10] This attack path is defined in Chap. 7, "Air Battle Analysis."

duced by an amount corresponding to the extra fuel consumed in accelerating from design combat speed to that actually used.

The remaining line through the operating region represents the Mach-number–load-factor combination which results in the minimum time to traverse the specified reattack path when the target bomber is flying at 500 knots.

Spotted over the operating region are several points representing speed–load-factor combinations used in the Air Battle Analysis of Chap. 7 in an attempt to determine a preferred mode of operation for this particular interceptor design. Various operating points were studied for other promising interceptor designs as well.

Whenever a particular interceptor has been used at an altitude differing from its design altitude, the change in fuel consumed during climb and combat has been considered in the modification of the combat-radius capability.

In general, after consideration of other factors of the over-all Air Defense Study, it was found that the desired interceptor aircraft were those having approximately a 15 per cent speed margin over the bomber, a transient load-factor capability of $1.5g$, and a combat radius between 150 and 300 nautical miles with 10 minutes of combat time. The optimum armament load, including installation, is between 1500 and 2000 lb.

CHAPTER 7
AIR BATTLE ANALYSIS

I. Introduction

An analysis of the effectiveness of an interceptor force was made as part of the Air Defense Study. Integrated systems, consisting of interceptors and their equipment and armament, were considered in defensive operations against various attacking bomber forces.[1] In the analysis bomber attrition was assumed to be the sole mission of the interceptor force. The results of the analysis are presented and discussed in this chapter.

The interceptor and bomber aircraft, their equipment and armament, the tactical doctrines considered, the techniques followed in synthesizing component studies of the Air Battle Analysis, and the analytical model of the air battle are described in detail in various RAND publications.[2]

II. Summary and Results of the Analysis

The Air Battle Analysis considered the physical properties and performance capabilities of interceptors and bombers, the capabilities of airborne and ground radar and computers, and interceptor and bomber weapon properties to determine the outcome of an air battle between these two types of aircraft.

This was done in the following way: First, the vectoring accuracy of the ground and airborne radar systems, and the physical characteristics and performance capabilities of the two aircraft, were studied to determine the probability that the interceptor would be vectored into a position and course such that its pilot would detect the bomber and be able to convert the detection into an attack. Secondly, the interceptor-bomber duel was studied, the results of the

[1] It is recognized that interceptors may also be used as tactical aircraft in other phases of a war. It was not possible to consider quantitatively the relative merits of the various interceptor designs examined in this study to assess their suitability for tactical employment. Consequently, these factors did not enter the numerical analysis. Such considerations could only be taken into account qualitatively in arriving at the conclusions of Chap. 2.

[2] These are listed in Appendix II.

duel being subsequently generalized into air battle results. The outcome of the duel is principally dependent on the weapons involved and on the initial orientation of the combatants.

The first step in developing an air battle model was accomplished by multiplying the duel outcome by the probability that the orientation studied in the duel would occur, and summing the product for all possible orientations.

The number of interceptors in the air battle was determined from an economic study of interceptor systems costs. Cost was introduced to permit comparisons of different interceptors on an equitable basis. As an interceptor's radius and ammunition-carrying capacity increases, so does its defense effectiveness. But simultaneously the size and cost of the interceptor increase and hence the number that can be bought for a fixed budget is reduced.

A bomber force was hypothesized which, together with the number of interceptors in the defensive force, determined the ratio of interceptors to bombers engaging in the air battle.

The air battle was studied by making a statistical analysis of a hypothetical engagement between the opposing forces, the engagement being designed to represent realistically the influence of as many as possible of the important factors. This statistical model had as its inputs:

1. The ratio of interceptors to bombers.
2. The interceptor and bomber survival probabilities resulting from the duel analysis.
3. The duration of the air battle.

For each combination of interceptor and bomber parameters, the analysis gave the fraction of bombers that were prevented from reaching the target, as a result of interceptor action, and the fraction of interceptors engaged in the battle that were lost to bomber defensive fire.

An illustrative set of result tabulation sheets is presented in Tables 5 through 8 (pages 122 through 125). Figure 35 (page 128) shows typical interceptor configurations and characteristics. Figure 36 (page 129) shows a schematic representation of the air battle and some typical results.

Fifty-seven tabulation sheets of this kind were calculated, representing more than ten thousand distinct combinations of bomber threat, interceptor performance, and interceptor armament.

NOTATION FOR TABLES 5 THROUGH 8

Speed-ratio: The ratio of interceptor to bomber speeds.

Load factor: Maneuvering load factor employed by the interceptor during positioning and attack.

Budget: One-quarter of the initial cost of the interceptor force, plus the annual maintenance cost of the force. Of the total force purchased, some cannot be engaged, some will not be committed, some will be down for maintenance, and some will abort, so that the number of interceptors in the actual air battle will be considerably fewer than those purchased. The budget figures shown correspond only to those interceptors that participate in the air battle.

F/B: Ratio of the numbers of interceptors to bombers in the air battle. The number of bombers is 200 in these tables.

K_B: Fraction of attacking bombers prevented from dropping bombs on the target because of interceptor action.

K_{F_A}: Cumulative fraction of original number of defending interceptors destroyed by bomber defensive fire in the air battle by the end of the specified pass. In addition, other interceptors receive nonlethal damage and are forced to withdraw from the air battle. For example, if an interceptor's AI radar is damaged by bomber defensive fire, the interceptor cannot continue the battle but can return successfully to base.

t_{c1}, t_{c2}: Afterburner-on time and air battle duration time. (Explained on pages 158 through 161.)

Some results of the Air Battle Analysis are presented now to show the results in terms of *kill potential,* an analytical concept designed to facilitate comparisons of defense weapons. Figure 37 (page 130) shows a comparison of various interceptor and armament choices for the period 1953–1957, when the main bomber threat is assumed to be the TU-4. For a later period (1957–1960) a family of generalized interceptors and various types of armament were compared.[4]

Table 5

CASE NO: 36 AMMO. LOAD: 6 TYPE: MX-904's vs STALIN ALT: 50,000 SPEED RATIO: 1.15 LOAD FACTOR: 1.4 EVASION: None OVERLOAD: None

Combat				Combat Radius: 100 N Mi								
Fuel Passes	Time (min)		Budget 10^7 Dollars		Salvos							
					1		2		3		6	
	t_{c1}	t_{c2}		F/B	K_B	K_{P_A}	K_B	K_{P_A}	K_B	K_{P_A}	K_B	K_{P_A}
1	.53	.53	5	.375	.18	0						
2	6.13	8.53		.371	.21		.22	0				
3	9.86	15.65		.370	.21		.26		.24	0		
4	13.59	22.55		.367	.21		.26		.28			
6	21.05	36.02	5	.363	.21		.27		.29		.26	0
1	.53	.53	10	.750	.32							
2	6.13	8.53		.742	.38		.42					
3	9.86	15.65		.740	.39		.48		.46			
4	13.59	22.55		.734	.39		.50		.53			
6	21.05	36.02	10	.725	.39		.50		.55		.51	0
1	.53	.53	20	1.500	.54							
2	6.13	8.53		1.484	.65		.71					
3	9.86	15.65		1.480	.67		.83		.79			
4	13.59	22.55		1.468	.67		.86		.90			
6	21.05	36.02	20	1.450	.67	0	.86	0	.94	0	.90	0

Combat				Combat Radius: 300 N Mi								
Fuel Passes	Time (min)		Budget 10^7 Dollars		Salvos							
					1		2		3		6	
	t_{c1}	t_{c2}		F/B	K_B	K_{P_A}	K_B	K_{P_A}	K_B	K_{P_A}	K_B	K_{P_A}
1	.53	.53	5	.371	.17	0						
2	6.13	8.53		.367	.20		.22	0				
3	9.86	15.65		.364	.21		.25		.24	0		
4	13.59	22.55		.360	.21		.26		.27			
6	21.05	36.02	5	.354	.21		.26		.28		.26	0
1	.53	.53	10	.741	.32							
2	6.13	8.53		.733	.38		.41					
3	9.86	15.65		.728	.39		.48		.45			
4	13.59	22.55		.720	.39		.49		.52			
6	21.05	36.02	10	.707	.38		.49		.54		.50	0
1	.53	.53	20	1.482	.53							
2	6.13	8.53		1.466	.65		.70					
3	9.86	15.65		1.456	.66		.82		.79			
4	13.59	22.55		1.440	.66		.84		.89			
6	21.05	36.02	20	1.414	.66	0	.84	0	.93	0	.89	0

Combat				Combat Radius: 500 N Mi								
Fuel Passes	Time (min)		Budget 10^7 Dollars		Salvos							
					1		2		3		6	
	t_{c1}	t_{c2}		F/B	K_B	K_{P_A}	K_B	K_{P_A}	K_B	K_{P_A}	K_B	K_{P_A}
1	.53	.53	5	.362	.17	0						
2	6.13	8.53		.357	.20		.21	0				
3	9.86	15.65		.354	.20		.25		.23	0		
4	13.59	22.55		.350	.20		.24		.26			
6	21.05	36.02	5	.340	.20		.25		.27		.25	0
1	.53	.53	10	.723	.31							
2	6.13	8.53		.713	.37		.40					
3	9.86	15.65		.707	.38		.47		.44			
4	13.59	22.55		.700	.38		.48		.50			
6	21.05	36.02	10	.680	.37		.47		.52		.48	0
1	.53	.53	20	1.446	.53							
2	6.13	8.53		1.426	.63		.69					
3	9.86	15.65		1.414	.65		.80		.77			
4	13.59	22.55		1.400	.65		.83		.87			
6	21.05	36.02	20	1.360	.64	0	.82	0	.91	0	.86	0

Table 6

CASE NO: 36 AMMO. LOAD: 12 TYPE: MX-904's vs STALIN ALT. 50,000 SPEED RATIO: 1.35 LOAD FACTOR: 1.1 EVASION: None OVERLOAD: None

Combat Radius: 100 N Mi

Fuel Passes	Time (min) t_{c1}	Time (min) t_{c2}	Budget 10^6 Dollars	F/B	Salvos 1 K_B	Salvos 1 K_{F_1}	Salvos 2 K_B	Salvos 2 K_{F_1}	Salvos 3 K_B	Salvos 3 K_{F_1}	Salvos 6 K_B	Salvos 6 K_{F_1}
1	.53	.53	5	.315	.20	0						
2	6.13	8.53		.309	.23		.29	0				
3	9.86	15.15		.304	.24		.34		.34	0		
4	13.59	22.55		.299	.23		.34		.38			
6	21.05	36.02	5	.290	.23		.34		.39		.38	0
1	.53	.53	10	.630	.36							
2	6.13	8.53		.616	.43		.53					
3	9.86	15.65		.607	.43		.61		.62			
4	13.59	22.55		.598	.43		.63		.70			
6	21.05	36.02	10	.580	.42		.62		.72		.72	0
1	.53	.53	20	1.260	.59							
2	6.13	8.35		1.232	.71		.81					
3	9.86	15.65		1.214	.73		.95		.95			
4	13.59	22.55		1.196	.73		.98		1.00			
6	21.05	39.02	20	1.160	.71	0	.98	0	1.00	0	1.00	0

Combat Radius: 300 N Mi

Fuel Passes	Budget 10^6 Dollars	F/B	Salvos 1 K_B	Salvos 1 K_{F_1}	Salvos 2 K_B	Salvos 2 K_{F_1}	Salvos 3 K_B	Salvos 3 K_{F_1}	Salvos 6 K_B	Salvos 6 K_{F_1}
1	5	.295	.19	0						
2		.289	.22		.27	0				
3		.285	.22		.32		.32	0		
4		.280	.22		.32		.36			
6	5	.271	.22		.32		.37		.36	0
1	10	.590	.34							
2		.577	.40		.50					
3		.570	.41		.58		.59			
4		.560	.41		.60		.66			
6	10	.542	.40		.59		.68		.68	0
1	20	1.180	.57							
2		1.154	.68		.81					
3		1.140	.70		.93		.93			
4		1.120	.69		.95		.99			
6	20	1.084	.68	0	.95	0	1.00	0	1.00	0

Combat Radius: 500 N Mi

Fuel Passes	Budget 10^6 Dollars	F/B	Salvos 1 K_B	Salvos 1 K_{F_1}	Salvos 2 K_B	Salvos 2 K_{F_1}	Salvos 3 K_B	Salvos 3 K_{F_1}	Salvos 6 K_B	Salvos 6 K_{F_1}
1	5	.279	.18	0						
2		.271	.21		.26	0				
3		.266	.21		.30		.30	0		
4		.260	.21		.30		.33			
6	5	.249	.20		.29		.34		.33	0
1	10	.557	.33							
2		.541	.38		.49					
3		.532	.39		.55		.55			
4		.520	.38		.56		.62			
6	10	.498	.37		.55		.64		.63	0
1	20	1.114	.55							
2		1.082	.65		.78					
3		1.061	.67		.90		.90			
4		1.040	.66		.92		.98			
6	20	.996	.64	0	.91	0	1.00	0	.99	0

Table 7

CASE NO: 36 AMMO. LOAD: 18 TYPE: MX-904's vs. STALIN ALT: 50,000 SPEED RATIO: 1.15 LOAD FACTOR: 1.4 EVASION: None OVERLOAD: None

Combat Radius: 100 N Mi

Fuel Passes	Combat Time (min) t_{c1}	t_{c2}	Budget 10^6 Dollars	F/B	Salvos 1 K_B	1 K_{P_A}	2 K_B	2 K_{P_A}	3 K_B	3 K_{P_A}	6 K_B	6 K_{P_A}
1	.53	.53	5	.233	.17	0						
2	6.13	8.53		.227	.19		.27	0				
3	9.86	15.65		.224	.20		.31		.32	0		
4	13.59	22.55		.220	.19		.31		.37			
6	21.05	36.02	5	.211	.19		.31		.37		.39	0
1	.53	.53	10	.465	.31							
2	6.13	8.53		.454	.36		.49					
3	9.86	15.65		.448	.36		.57		.60			
4	13.59	22.55		.439	.36		.58		.68			
6	21.05	36.02	10	.422	.35		.57		.69		.73	0
1	.53	.53	20	.930	.52							
2	6.13	8.53		.908	.62		.80					
3	9.86	15.65		.896	.63		.91		.93			
4	13.59	22.55		.878	.63		.94		1.00			
6	21.05	36.07	20	.844	.61	0	.93	0	1.00	0	1.00	0

Combat Radius: 300 N Mi

Fuel Passes	t_{c1}	t_{c2}	Budget 10^6 Dollars	F/B	Salvos 1 K_B	1 K_{P_A}	2 K_B	2 K_{P_A}	3 K_B	3 K_{P_A}	6 K_B	6 K_{P_A}
1	.53	.53	5	.216	.16	0						
2	6.13	8.53		.210	.18		.25	0				
3	9.86	15.65		.206	.18		.28		.30	0		
4	13.59	22.55		.201	.18		.29		.34			
6	21.05	36.02	5	.192	.17		.28		.34		.35	0
1	.53	.53	10	.432	.29							
2	6.13	8.53		.420	.34		.46					
3	9.86	15.65		.412	.34		.53		.56			
4	13.59	22.55		.402	.33		.54		.63			
6	21.05	36.02	10	.383	.32		.52		.64		.67	0
1	.53	.53	20	.864	.49							
2	6.13	8.53		.840	.58		.76					
3	9.86	15.65		.824	.60		.88		.90			
4	13.59	22.55		.804	.59		.90		.98			
6	21.05	36.07	20	.766	.57	0	.89	0	1.00	0	1.00	0

Combat Radius: 500 N Mi

Fuel Passes	t_{c1}	t_{c2}	Budget 10^6 Dollars	F/B	Salvos 1 K_B	1 K_{P_A}	2 K_B	2 K_{P_A}	3 K_B	3 K_{P_A}	6 K_B	6 K_{P_A}
1	.53	.53	5	.199	.14	0						
2	6.13	8.53		.194	.17		.23	0				
3	9.86	15.65		.189	.17		.26		.28	0		
4	13.59	22.55		.185	.17		.27		.31			
6	21.05	36.02	5	.173	.16		.25		.31		.32	0
1	.53	.53	10	.398	.27							
2	6.13	8.53		.387	.31		.43					
3	9.86	15.65		.378	.31		.49		.52			
4	13.59	22.55		.369	.31		.50		.58			
6	21.05	36.02	10	.345	.29		.48		.58		.61	0
1	.53	.53	20	.796	.46							
2	6.13	8.53		.774	.55		.73					
3	9.86	15.65		.756	.56		.83		.86			
4	13.59	22.55		.738	.55		.86		.95			
6	21.05	36.07	20	.690	.52	0	.83	0	.97	0	.99	0

Table 8

CASE NO: 54 — AMMO. LOAD: 12 — TYPE: MX-904's vs LENIN — ALT: 50,000 — SPEED RATIO: 1.15 — LOAD FACTOR: 1.5 — EVASION: None — OVERLOAD: None

Combat Radius: 100 N Mi

Fuel Passes	Combat Time (min) t_{c1}	t_{c2}	Budget 10^7 Dollars	F/B	Salvos 1 K_H	K_{P_1}	Salvos 2 K_H	K_{P_1}	Salvos 3 K_H	K_{P_1}	Salvos 6 K_H	K_{P_1}
1	.28	.28	5	.308	.11	0						
2	6.47	8.07		.288	.15		.13	0				
3	11.34	15.20		.270	.16		.17		.14	0		
4	16.21	22.18		.252	.15		.18		.16			
6	25.95	35.93	5	.216	.14		.17		.17		.12	0
1	.28	.28	10	.616	.21							
2	6.47	8.07		.575	.28		.25					
3	11.34	15.20		.540	.30		.32		.26			
4	16.21	22.18		.504	.30		.34		.31			
6	25.95	35.93	10	.432	.26		.33		.34		.24	0
1	.28	.28	20	1.232	.37							
2	6.47	8.07		1.150	.51		.47					
3	11.34	15.20		1.080	.55		.59		.50			
4	16.21	22.18		1.008	.55		.64		.59			
6	25.95	35.93	20	.864	.50	0	.62	0	.64	0	.46	0

Combat Radius: 300 N Mi

Fuel Passes	Combat Time (min) t_{c1}	t_{c2}	Budget 10^7 Dollars	F/B	Salvos 1 K_H	K_{P_1}	Salvos 2 K_H	K_{P_1}	Salvos 3 K_H	K_{P_1}	Salvos 6 K_H	K_{P_1}
1	.28	.28	5	.279	.10	0						
2	6.47	8.07		.256	.13		.12	0				
3	11.34	15.20		.236	.14		.15		.12	0		
4	16.21	22.18		.216	.13		.15		.14			
6	25.95	35.93	5	.171	.11		.13		.14		.10	0
1	.28	.28	10	.558	.19							
2	6.47	8.07		.512	.25		.23					
3	11.34	15.20		.472	.27		.28		.23			
4	16.21	22.18		.431	.26		.30		.27			
6	25.95	35.93	10	.342	.21		.26		.27		.19	0
1	.28	.28	20	1.116	.34							
2	6.47	8.07		1.024	.46		.42					
3	11.34	15.20		.944	.49		.53		.44			
4	16.21	22.18		.862	.48		.56		.51			
6	25.95	35.93	20	.684	.40	0	.50	0	.52	0	.37	0

Combat Radius: 500 N Mi

Fuel Passes	Combat Time (min) t_{c1}	t_{c2}	Budget 10^7 Dollars	F/B	Salvos 1 K_H	K_{P_1}	Salvos 2 K_H	K_{P_1}	Salvos 3 K_H	K_{P_1}	Salvos 6 K_H	K_{P_1}
1	.28	.28	5	.246	.09	0						
2	6.47	8.07		.216	.11		.10	0				
3	11.34	15.20		.191	.11		.12		.10	0		
4	16.21	22.18		.164	.10		.12		.11			
6	25.95	35.93	5	—	—		—		—		—	0
1	.28	.28	10	.491	.17							
2	6.47	8.07		.431	.22		.19					
3	11.34	15.20		.381	.22		.23		.19			
4	16.21	22.18		.327	.20		.23		.21			
6	25.95	35.93	10	—	—		—		—		—	0
1	.28	.28	20	.982	.31							
2	6.47	8.07		.862	.40		.36					
3	11.34	15.20		.762	.41		.44		.36			
4	16.21	22.18		.654	.38		.44		.40			
6	25.95	35.93	20	—	—	0	—	0	—	0	—	0

KILL POTENTIAL

Kill potential is expressed numerically as the maximum number of bombers which would be killed before the bomb-release line if all the interceptor defenses of all the targets were brought to bear on an extremely large saturation raid. It includes the effects of weapon commitment, availability, aborts, and minimal operational degradation but not the effects of surprise* or of enemy use of electronic countermeasures. This definition of kill potential is repeated from Chap. 2, where it was used in connection with Figs. 7, 8, and 9. Kill potential is always given for a specified defense budget, i.e., the total budget for area-defense weapons and the budget per target for local-defense weapons. Note that the above concept does not reflect the greater effectiveness of weapons having longer combat radius, since "all the defenses of all the targets" are brought to bear on the raid. Although kill potential can be used *directly* only in a comparison of weapons of equal radius, with an awareness of the effect on cost of varying radius it permits elimination of certain cases without detailed computation. It is also used in conjunction with measures of the effects of radius in comparing less obvious cases of dissimilar weapons. This part of the study is reported in Part II.

Kill potential (for $1 billion) is derived from Tables 5 through 8 by the following relation:

$$\text{Kill potential (for \$1 billion)} = K_B \cdot B \cdot F_{ar} \cdot F_{ab} \cdot F_{sc} \cdot \frac{10^9}{C_0},$$

where K_B is the fraction of attacking bombers prevented from dropping bombs on the target because of interceptor action. It is found in the preceding tables or in the more complete tables of RM-572. The lowest budget section shown in a table should be used for this to avoid the effects of running out of bombers; these effects are excluded by the definition.

B is the number of bombers hypothesized for the tables. This number is 200 for all the tables given here.

F_{ar} is a factor to account for availability of fighters. This was assumed to be two-thirds.

F_{ab} is a factor to account for aborts and gross errors of the fighters. This was assumed to be 0.89.

F_{sr} is an additional factor used to account for a commitment of less than 100 per cent of the fighter forces because of the air commander's incomplete knowledge of enemy feints, particularly near the edge of radar cover. It was assumed to be 0.85 when averaged over all the ZI. (This matter will be discussed more completely in Part II.)

C_0 is the budget level for which K_B was found (from Col. 4 of the table).

In addition to the above factors, it was necessary, at the time of bringing together the component parts of the Defense Systems Analysis, to make certain adjustments and to account for various omissions which could be handled most efficiently at this stage.†

The concept of kill potential was a very useful one in the synthesis work of RAND's study. The component studies (such as the Air Battle Analysis described in this chapter) can be thought of as having a set of kill potentials as their numerical outputs, whereas the synthesis of Part II takes these as its inputs.

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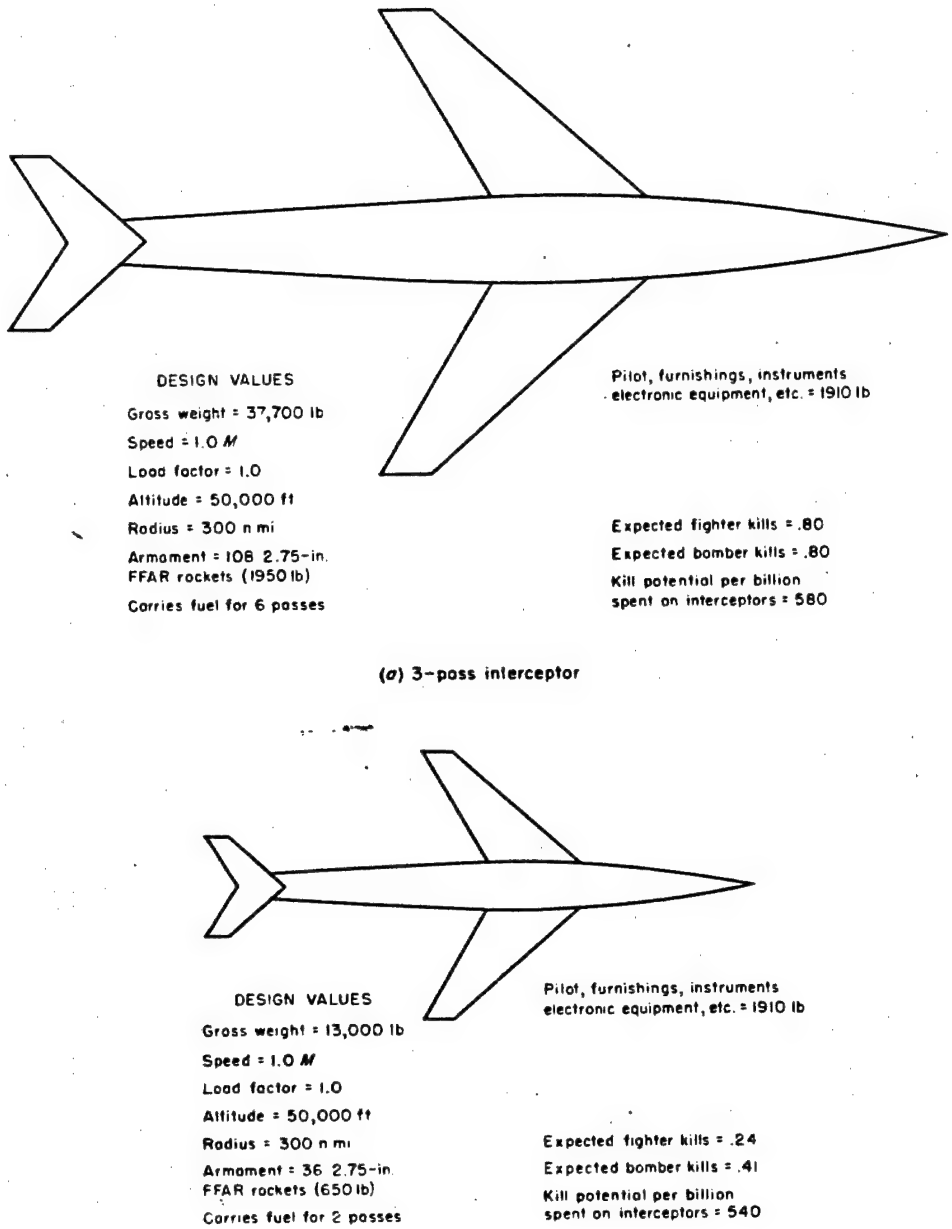
* The estimates of availability, aborts, etc., were based on an assumption of well-trained forces operating under "steady-state" conditions.

† These included an increase in kill potential by a factor of about 1.04 for all cases involving rocket-armed interceptors; the original costing of these interceptors included missile-armament maintenance personnel. Costs of repurchasing shot-down fighters, of training additional pilots, and of replacing expended missiles were inserted at this point—these values were never appreciable. The only important factor of this group was that which accounted for a "best guess" of the effect of fuzing errors for armaments using VT fuzes. The original air battle calculations assume no fuzing error, i.e., detonation at the optimum point. There were few data on which to base an estimate of expected fuze errors, so their inclusion was left to the last, and as an approximation, kill potential was multiplied by the following factors:

Armament	Bomber		
	Stalin		Lenin
	No evasion	Evasion	No evasion
318-lb fragmenting rocket	.94	.82	. . .
400-lb generalized missile	.93	.88	.68



(b) 1-pass interceptor

Fig. 35—Interceptor configurations and characteristics

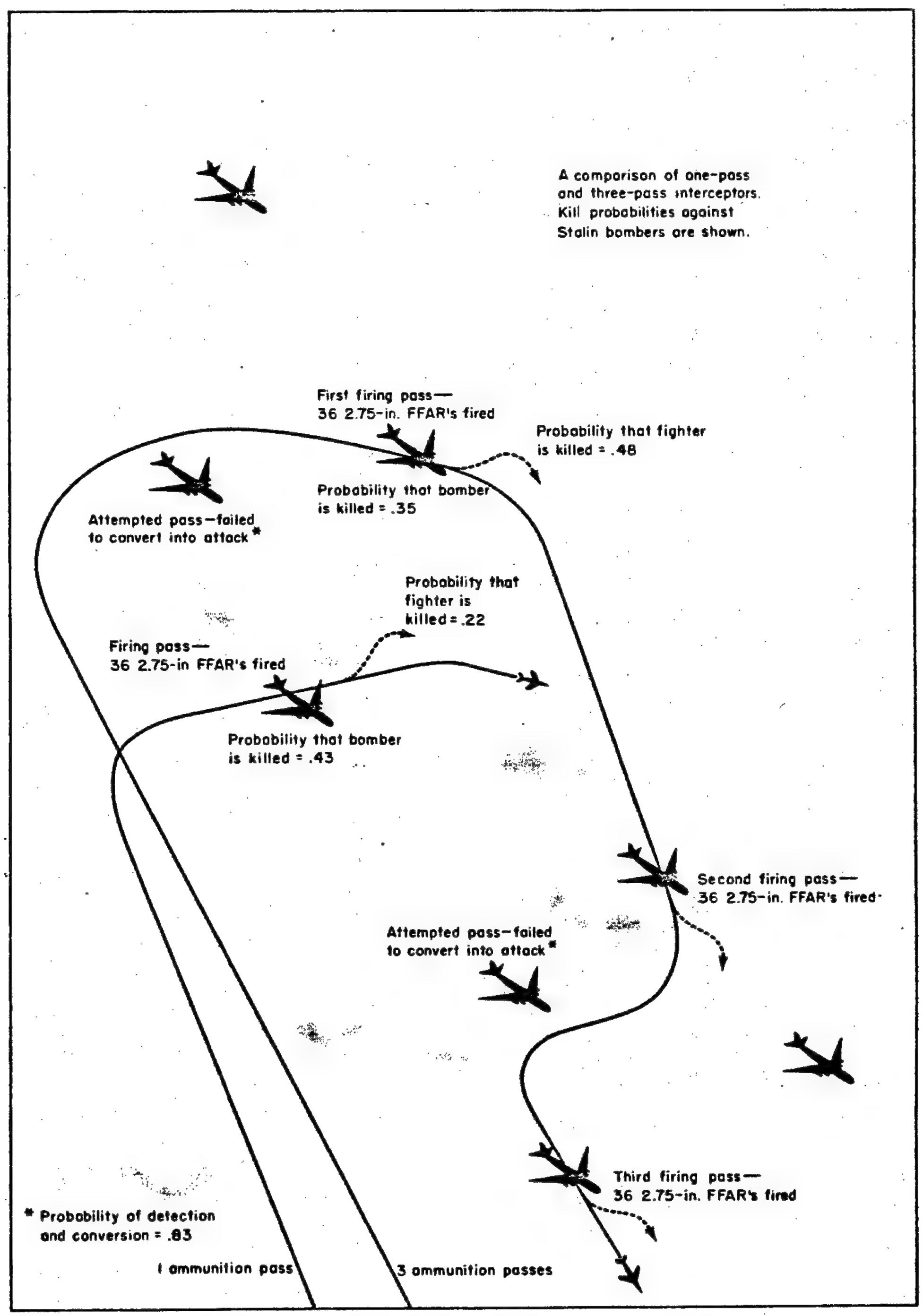


Fig. 36—Schematic representation of an air battle

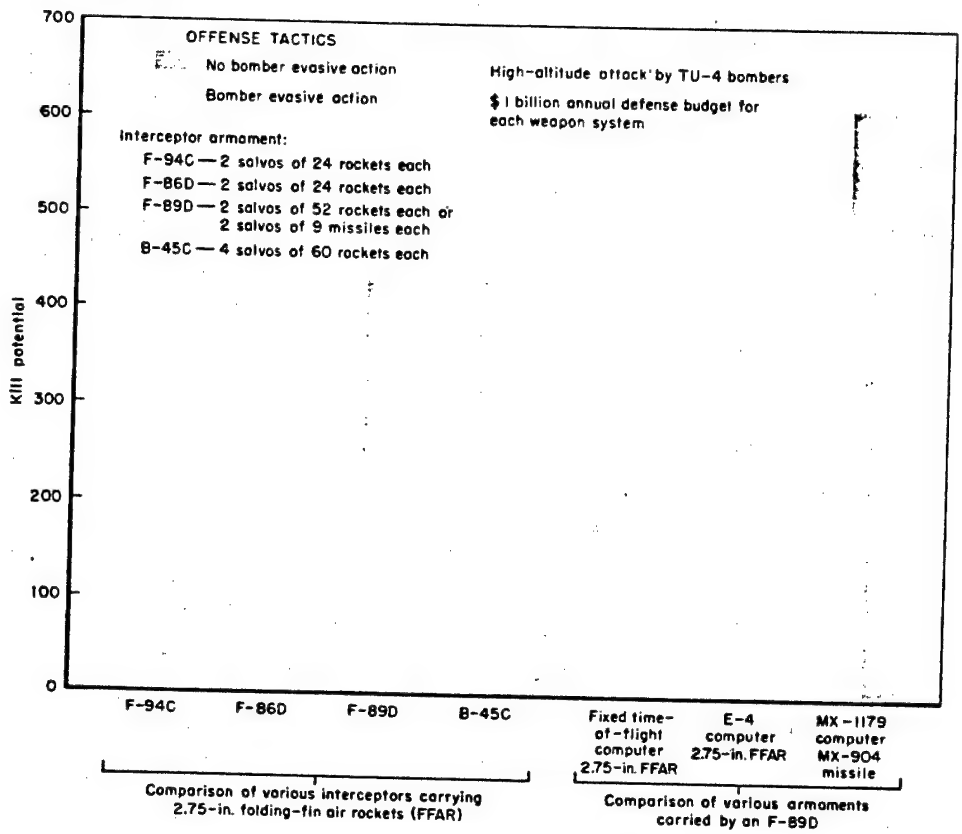


Fig. 37—First-generation interceptors vs TU-4 bomber

For each computer and sight type, the total amount of armament carried, the number of firing passes (within some combat-time restriction), and the interceptor design characteristics were chosen to give maximum effectiveness. The results of such a comparison, when the Stalin bomber was assumed to be the threat, are shown in Fig. 38. Similar results, comparing interceptors defending against the Lenin bomber, are shown in Fig. 39. For one particular armament type and amount—twelve MX-904 missiles—the effect of varying the number of firing passes and amount of combat time (at constant interceptor speed, load factor, radius, and altitude capability) is shown in Fig. 40 for interceptors defending against Stalin bombers.[5] The effect of varying the armament load and number of firing passes was examined, both for a combat time

[5] This illustration neglects the fact that increased combat time increases the early-warning-radar cost and reduces the over-all system effectiveness. This effect is not serious for interceptors based inland. For coastal defense, the situation is analyzed separately in Chap. 11, "Radar Networks," and in Part II, Chap. 15, "Selection of Radius and Combat Time—Area-Defense Weapons."

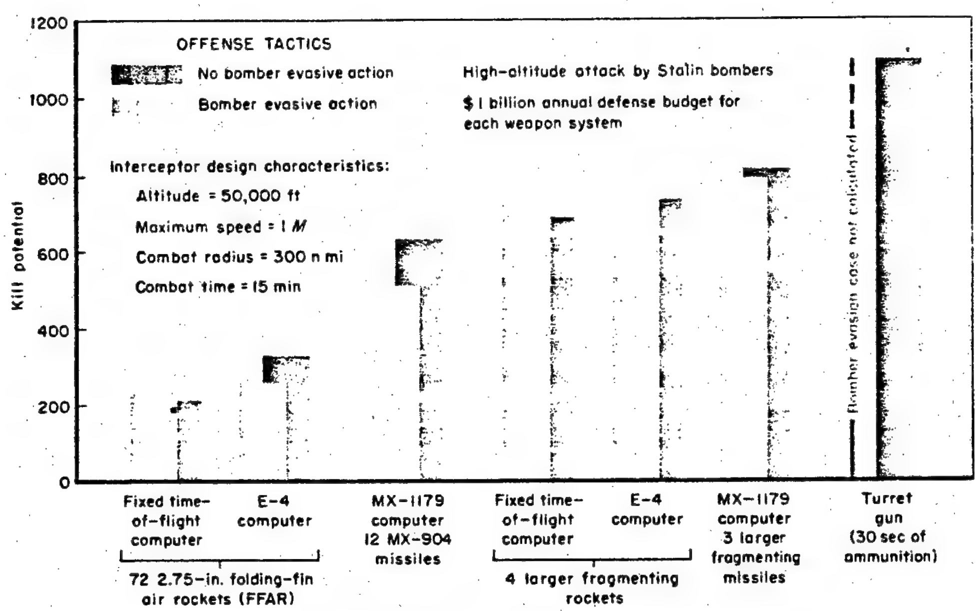


Fig. 38—Second-generation interceptor vs Stalin bomber

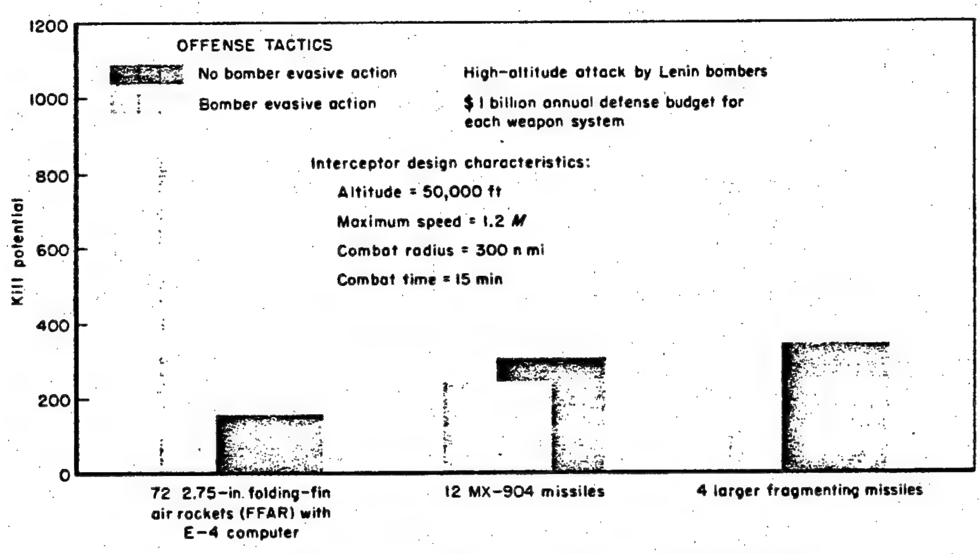


Fig. 39—Second-generation interceptor vs Lenin bomber

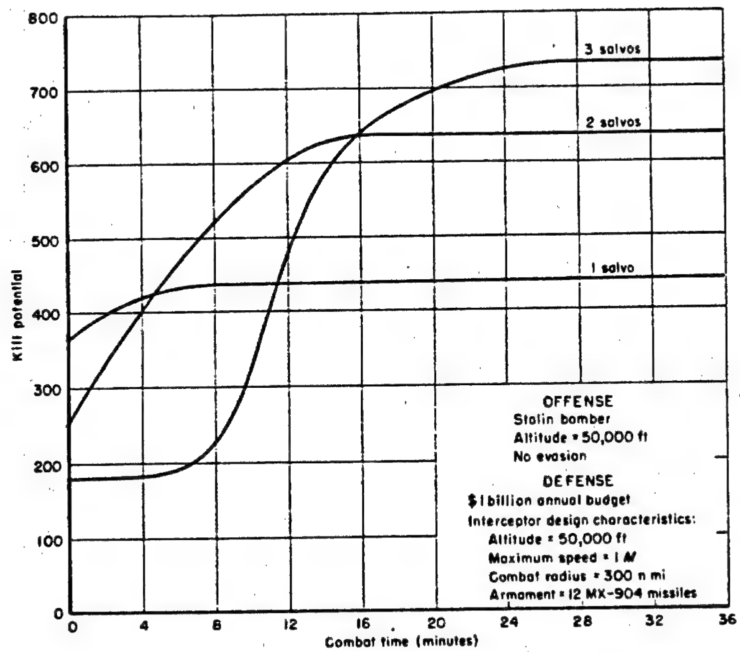


Fig. 40—Effect of combat time and number of salvos on interceptor effectiveness

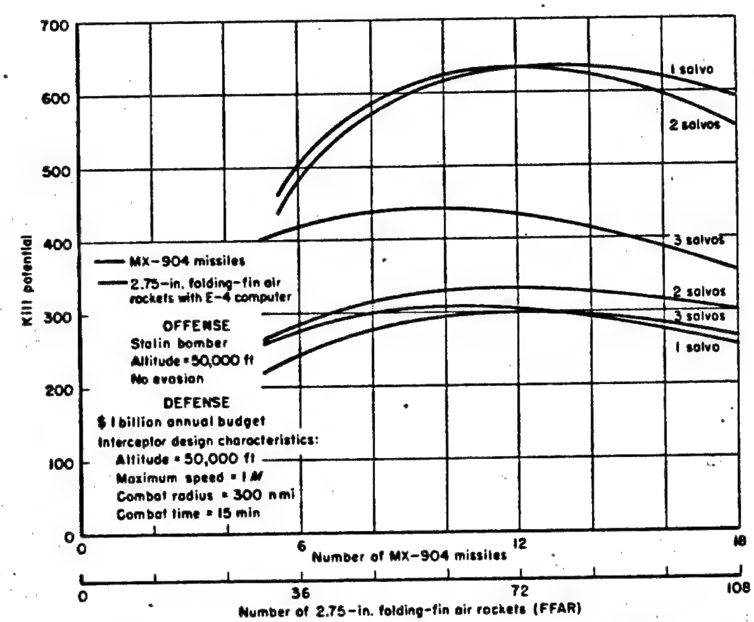


Fig. 41—Effect of armament amount and number of salvos on interceptor effectiveness—Stalin bomber

sufficiently long to permit several attempted firing passes (Fig. 41) and for a combat time sufficiently short to permit only one attempted pass (Fig. 42). Figure 43 shows the results of a similar examination of interceptors having longer combat time defending against the Lenin bomber. The lower interceptor kill potential against the Lenin resulted partly from the higher cost of a faster interceptor (and the smaller size of the interceptor force which this occasions) and partly from the lower vulnerability of the Lenin bomber because of its smaller size. Of course, since the Lenin bomber is not assumed to be capable of long-range strategic attacks without multiple refuelings (or some other form of assistance), and since it would be of more advanced design, we might assume fewer bombers in the attacking force, so that the lower effectiveness of the interceptor might not be significant.

The preferred interceptor speed margin and load factor at combat altitude were investigated for combat with the assumed bomber threats. In each case, the results indicated that a speed margin of approximately 15 per cent and a transient load-factor capability[6] of $1.5g$ are required to ensure satisfactory collision-course attacks with a reasonable number of repeat-attack opportunities.

The time-to-climb-to-altitude of these interceptors is, of course, related to the above parameters. This aspect of interceptor effectiveness is discussed in the section on radar-interceptor optimization, Chap. 15.

An important difference not shown in these illustrations exists. The missile-armed interceptors are assumed to launch their weapons at ranges such that they are not shot down in the air battle, whereas interceptors equipped with other armaments are lost because they fire within range of the bomber defensive weapons. Since interceptor losses result in the loss of some pilots,[7] it is impossible to make a valid comparison in terms of cost alone. This difference is taken into account *numerically* by adding to the cost of the interceptor squadrons the purchase cost of interceptors replaced and the training costs of replacement pilots.

Some of the other important differences in interceptors that are not shown by the kill-potential computations are differences in (1) their low-altitude capability, (2) their ability to resolve closely spaced bombers, (3) their reaction to ECM, and (4) the problems of technical feasibility in getting them operational by a given date. All of these differences, while not treated numerically, were taken into account in arriving at the conclusions of Chap. 2.

[6] The load factor that the interceptor can pull for a limited time in a transient condition without losing altitude.

[7] Approximately 20 per cent according to the vulnerability studies made.

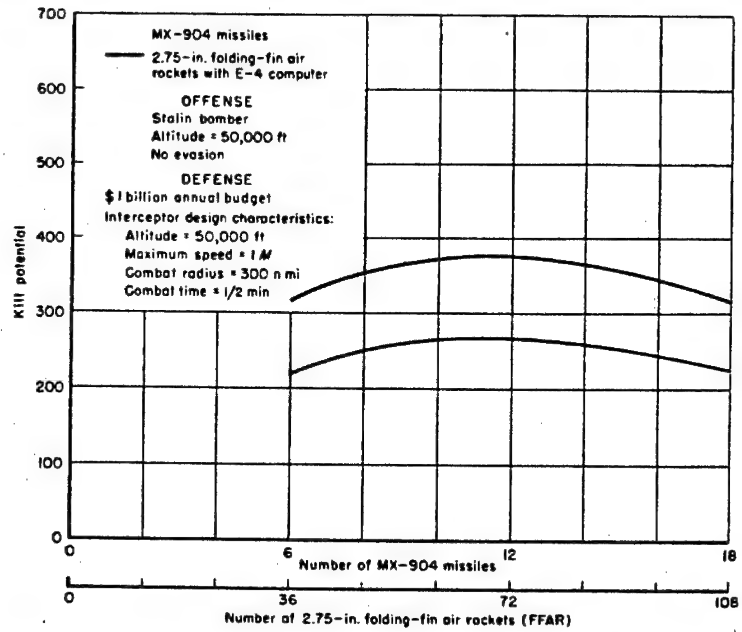


Fig. 42—Effectiveness of interceptors which are limited to one pass

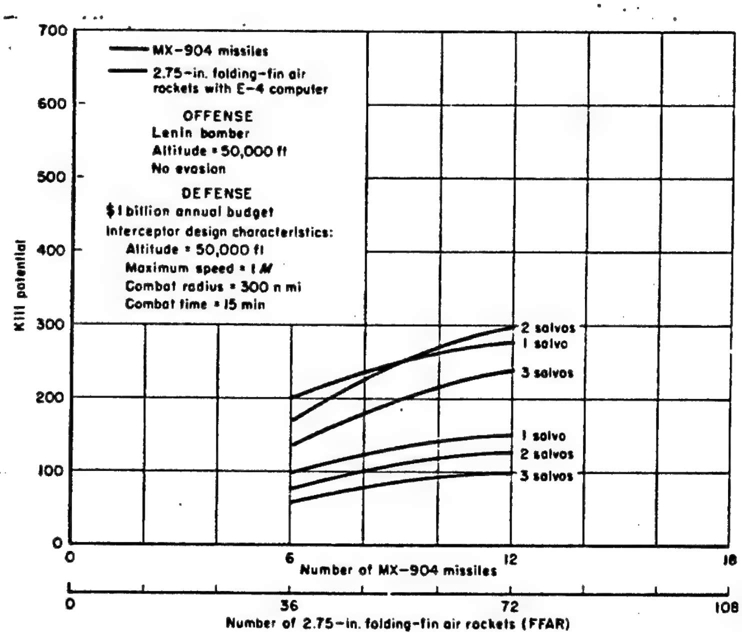


Fig. 43—Effect of armament amount and number of salvos on interceptor effectiveness—Lenin bomber

III. Interpretation of Air Battle Calculations

In making this study, certain simplifying assumptions were made. It is believed, however, that the principal design and operational factors affecting the outcome of the air battle have been correctly assessed. In particular, the calculations do not account for the various formations of bomber and interceptor forces as they come together. Instead, the engagement of forces is essentially a compound of duels between each bomber and a number of interceptors defined by a probability distribution about a most probable number of interceptors.

Further major simplifications were introduced. All bombers were assumed to be equally desirable targets; a distinction was not made between an interceptor making a second (or subsequent) pass on the same bomber or on a different bomber.[8] (However, the interceptor's time in combat, and the duration of the air battle, were calculated on the basis of the number of passes made by the interceptor and the time consumed in a reattack on the same bomber.) Also, the outcome of the air battle, expressed as the fraction of the attacking bombers killed, was assumed to be independent of the total number of interceptors or bombers involved and dependent only on the ratio of these numbers.[9]

Because of simplifications of this kind, the interceptor and bomber attrition figures produced by the calculations must be regarded as yardstick figures and not as exact attrition predictions. Although it is believed that the calculations correctly and equitably compare one interceptor force with another, and permit the preferred equipment to be found, they do not provide a realistic forecast of the attrition the system might achieve.

IV. Prime Variables Which Affect Interceptor Effectiveness

Excluding interceptor weapon characteristics, the variables which most affect interceptor effectiveness are conditions of visibility, enemy fighter escorts, the attack altitude, enemy bomber characteristics, enemy evasive maneuvers, and the type of attack employed by the interceptor.[10]

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[8] The distinction is not necessary so long as the spacing between bombers is not greater than roughly 3 miles.

[9] This excludes consideration of the saturation of the control facilities of the radar network. This question is discussed in Chap. 11.

VISIBILITY

Although the air battle may take place under conditions of good or poor visibility, in daytime or at night, the present study considered mainly all-weather interceptors equipped with radar for AI search and weapon-laying.

When an air battle takes place under conditions of poor visibility, electronic equipment is required in the air and on the ground. Although the bombers could fly in loose cells under such conditions, they would not be close enough to give one another effective co-ordinated firepower protection. Interceptors could be vectored in groups of two or three to reduce the burden on the ground controllers, but essentially independent attacks would be made against individual bombers.

Under conditions of good visibility, the bombers might try defensive formations, but it was felt that with the interceptor speeds involved, and since the collision-course interceptor armament would permit all-around attacks, such formations would be relatively ineffective. It was assumed that the interceptors would use their AI radar equipment even under good visibility conditions because the range performance of the advanced equipment considered is superior to visual-range performance.

The main difference between attacks under conditions of good and bad visibility is that, against a daylight attack, the defense can mount large numbers of day fighters in addition to the all-weather interceptors. Airplane for airplane, the all-weather interceptor, because of its radar equipment, is more effective than the day fighter under conditions of good visibility. The possibility that day fighters may appear in combat along with the all-weather interceptors has no influence on the selection of the preferred all-weather interceptor; hence, for the purposes of recommending armaments and design characteristics of the all-weather interceptor, it was felt to be sufficient to analyze combat under poor visibility conditions. In addition, it is believed to be fairly likely that the Soviets will make their attacks at night or when poor conditions of visibility are expected to exist.

ENEMY ESCORTS

Because of the distances involved in a Soviet attack on the United States, it was assumed that the bombers would not have parasite or escort fighter protection. However, the use of bombers as escorts was considered because this would increase the probability that the bomb carriers would survive to bomb.

In addition, since they would not carry bombs, the escort bombers were assumed to carry considerable chaff, equipment for jamming our electronic equipment, or other devices for their own protection.

ATTACK ALTITUDE

The enemy bombers were assumed to be capable of attacking at any altitude, ranging from their maximum combat altitude (35,000 to 50,000 ft) to a low-altitude limit of 1500 ft over land under conditions of poor visibility, 200 ft over land under conditions of good visibility, or 200 ft over the ocean for any condition of visibility. However, only the limiting altitudes were investigated, since it was felt that these are the critical altitudes affecting the defense.

For the low altitudes, the question of the effectiveness of the ground-radar network or Ground Observer Corps, the performance of the AI search and track gear, and the performance of the missile seekers and VT fuzes are important. However, these items were not reduced to quantitative terms because sufficient reliable operational data are lacking and because of the difficulty of theoretical analyses of such problems. *The low-altitude attack was found to be a very serious threat* to this country and particular attention was given to the defense-weapon problems which it poses. This problem is discussed in more detail in Chap. 12.

ENEMY THREATS

The enemy bombers considered were the TU-4, the Stalin (high-subsonic speed) and the Lenin (supersonic combat speed). It was assumed that interceptors would be designed specifically to combat either the Stalin or the Lenin bomber. In addition, calculations were made of the capability of the Lenin-matched interceptor against the Stalin, and of the Stalin-matched interceptor against the TU-4.

ENEMY EVASIVE MANEUVERS

The bombers were given the capability of instituting evasive maneuvers at any time. These maneuvers were assumed to take place in a vertical plane and were limited to $\pm 1.0g$ acceleration. It was assumed that these maneuvers would be made so infrequently that some loss in altitude could be tolerated during the maneuver.

TYPE OF ATTACK EMPLOYED BY THE INTERCEPTOR

The bombers were assumed to fly an essentially straight and level course except during evasion. It was assumed that the interceptor would be ordered by the GCI radar director to the bomber's altitude and vectored on a slightly offset straight collision course perpendicular to the bomber's course.[11] The offset is required because the interceptor's armament fires prior to collision and travels faster than the interceptor.

The principal reason for considering only collision-course attacks is the present Air Force emphasis on the design and development of air-to-air rockets and missiles and on airborne radar and fire-control gear for collision-course attacks. The desirability of collision tactics for these armaments can be independently deduced: it is highly desirable for the interceptor to avoid the bomber's defensive fire, particularly from the tail turret. To achieve this the interceptor is forced to make large deflection attacks. But interceptor load-factor capabilities, particularly at high altitude, severely reduce the time that the bomber can be tracked within range of the forward-firing fixed armament of the interceptor. Thus, high-rate-of-fire armaments are indicated.[12] It is substantially immaterial to the kinematics of the interception problem whether the interceptor is flying a straight or a curved course at the instant of fire. However, if the course is curved, the accelerations involved seriously complicate the fire-control problem. Hence, a straight offset collision-course tactic is believed to be most desirable.

Once the interceptor is on the predicted collision course, as given by the GCI radar director, an AI radar search around the expected bomber position is begun. If the bomber is detected, the interceptor pilot determines his own relative position and decides whether or not to attack. In the study it was assumed that he would always attack unless by so doing he would end the attack within 30° of the bomber track. This 30° exclusion was made because the interceptor survival probability is quite low for approaches astern of the bomber and the interceptor effectiveness is low for nearly head-on attacks. It was assumed that if the interceptor did not detect the bomber in time to attack or

[11] The choice of this perpendicular course was a compromise between lower probabilities of AI detection and conversion from ahead and lower probabilities of interceptor survival from astern.

[12] An exception to this is the flexible turret gun. RAND calculations indicate that a twin 30-mm turret gun is preferred, and this armament is subsequently described. The primary requirement for full exploitation of gun capability is provision, in the tactic, for sufficient time within effective gun range for the maximum burst length to be fired. This requirement is fulfilled by the collision tactic being described when the guns are fired continuously from 7 to 2 sec before collision would occur. (See "The Duel," page 145.)

was incapable of attacking, he would fly across the bomber's path, begin a turn toward the bomber, and attempt a repeat attack on a collision track 45° off the bomber's course.[13] Those interceptors successfully executing a firing pass were assumed to proceed without changing course until they reached the bomber track, where they would make a turn toward the bomber and attempt a subsequent attack at a course difference of 45°. The second and subsequent passes were assumed to be made by crossing back and forth over the bomber track, as depicted in Fig. 44. It is realized that the choice of attack angles is somewhat arbitrary, but time did not permit the calculation of other angles and for the purpose of *armament comparison* the case considered is felt to be sufficient.

The attack paths used in the air battle calculations were limited to a horizontal plane but are applicable to moderate climbing or diving attacks. However, other types of attack paths have been investigated in some detail. Two of these paths, both in the vertical plane, are the "zoom" (or "snap up") and the "high-angle climb." These two paths differ only in degree, the "zoom" involving a large change in altitude and relatively large deceleration, and the "high-angle climb" involving smaller changes in altitude and less deceleration. (See Fig. 45.)

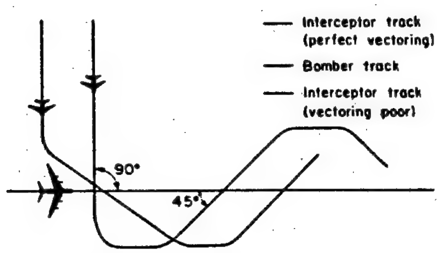

Fig. 44—Schematic diagram of interceptor tactic

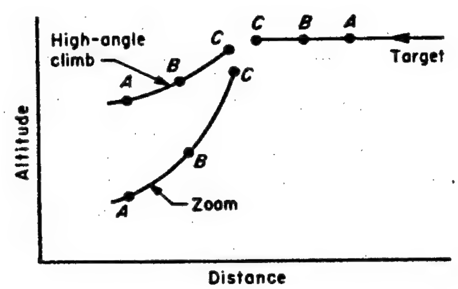

Fig. 45—"Zoom" and "high-angle" climbs

In general, the "zoom" attack is started at an altitude close to the altitude for maximum interceptor speed. By using this tactic, the interceptor can reach altitudes in excess of its steady-state ceiling. However, the effectiveness of such an attack is rather critically dependent on the start of the attack being made at the proper instant. Also, since large decelerations are involved, the computing problem is severe. As far as is known, no computer applicable to this type of

[13] For subsequent attacks, a rear-quarter approach was assumed in order to reduce the re-attack time.

attack is under development. If developed, such a computer would contribute materially to interceptor effectiveness.

The "high-angle-climb" attack is initiated approximately 5000 to 10,000 ft below the bomber. In this type of attack the primary purpose is to hold the interceptor in a transient nose-up position long enough to fire the armament. If the interceptor is armed with fairly long-range air-to-air missiles, it does not have to reach the bomber's altitude. However, the solution and settling times of the proposed computers are so long (approximately 5 to 10 sec) that an airplane which could make such an attack would also be capable of level flight at the bomber's altitude. Even if a computer suitable for use with this tactic did exist, such a tactic would not be appreciably better than the horizonal-plane attack considered in this study.

V. Components of the Air Battle Study

AI RADAR DETECTION

A study[14] was made of the expected search performance of the AN/APG-37 type of airborne radar based on an analysis[15] of the theoretical range capabilities degraded for field performance. This analysis considered the probability, as a function of the range and aspect of the target, that on any one radar-scan a target blip would be seen. The criterion of detection was that the target should appear as a blip on two successive scans. The cumulative probability of detection was then determined as a function of interceptor position relative to the bomber and to the angle between the bomber and interceptor tracks. The vectoring errors of the GCI system were evaluated and expressed as an equivalent error in the interceptor's position perpendicular to its own track.

Until about 1955, vectoring will probably be done manually from the radar data furnished by the AN/CPS-6B or AN/FPS-3 radars. The standard deviation of the vectoring error for this time period is estimated to be ± 1.5 nautical miles. After 1955, automatic equipment will be used. This may include the semiautomatic GCI equipment being developed by Rome Air Development

Center or the large digital computers envisaged by Project Lincoln. Furthermore, the AN/CPS-6B and AN/FPS-3 radars will eventually be replaced by other and possibly more accurate radars. By means of these improvements the vectoring error can probably be reduced to about 3000 ft by 1958 or 1960, neglecting problems of target resolution.

Some exploratory calculations were made using a vectoring error of 3000 ft to determine its effect on interceptor effectiveness. Largely because of the ample range of the AI radar, the effect was small. Because of this, and since it may be more practical to have large resolution blocks and less data-smoothing in the interceptor control system, the original ± 1.5-nautical-mile error was considered to apply to all time periods of the study. (However, this does not apply in the case of surface-to-air missiles, where seeker ranges of area-defense missiles are marginal and where data-smoothing will be more attractive. Also, if the offense weapon is a missile, the spacing will probably be greater, permitting greater accuracy. As stated in Chap. 8, these ground vectoring errors of missiles were taken to be 3000 to 4000 ft, depending on the time period.)

Figure 46 illustrates the nature of the assumed vectoring error. In this figure, the height of the shaded region at any point on the line *A-B* is a measure of the probability that the interceptor will pass through that point in approaching the bomber. The combining of the probability of various approaches to the bomber with the probability of AI radar detection at various points around the bomber results in the determination of the probability that AI radar detection will in fact take place at various locations around the bomber.

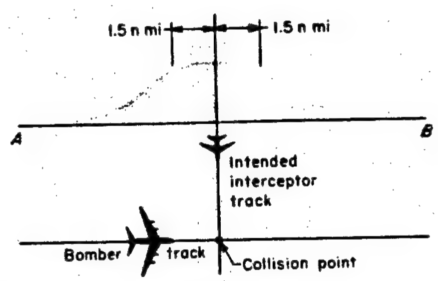

Fig. 46—Distribution of vectoring errors

CONVERSION BARRIERS

Barriers were determined to define the limits of the regions within which the interceptor could successfully execute the prescribed offset collision-course attack. These were developed by using the following assumptions: the interceptor would be directed on a horizontal course at a definite intended course-difference to the bomber. After AI detection of the bomber, the interceptor would turn at constant load factor onto a collision course with the aiming point and then fly a straight-line path to the firing point. For successful firing, this

portion of the path must be greater than some minimum length determined by the fire-control and weapon characteristics.[16]

The complete conversion barrier consists of segments of one or more of the following component barriers:

- Contour of minimum permissible distance from completion of turns to the collision point. (This minimum distance is a function of the weapon and computer characteristics.)
- Contours corresponding to the maximum maneuver limitations of the interceptor. (If the interceptor starts to turn inside this barrier, it will not be able to turn sharply enough to arrive at a collision point that is outside the minimum-distance barrier.)
- Contours for minimum angular course-difference allowable during firing run. (The interceptor would not press home an attack if, during the firing run, its course was within 30° of the bomber course.)
- Contours of maximum AI radar side-angle vision. (Obviously, the interceptor cannot detect and convert if the bomber is outside the field of view of the AI radar.)

Typical conversion barriers are plotted in Fig. 47. The barriers are drawn in bomber space coordinates which move with the bomber.

The probability of AI detection before reaching these barriers was then summed over all the possible ways that the interceptor could arrive at the barriers (as a result of the vectoring errors), and the over-all probability of AI detection and conversion to a firing run was determined. Typical results are presented in Fig. 48.

These results are based entirely on theoretical estimates except for the introduction of an operational degradation factor deduced from the range performance of the AI radar. It was necessary to produce the estimates on this theoretical basis in order to evaluate accurately the effect of interceptor speed ratio, load factor, etc., on the results and in order to predict the performance of untried equipment which promises to be markedly improved over World War II equipment. It was felt that direct use of operational data from World

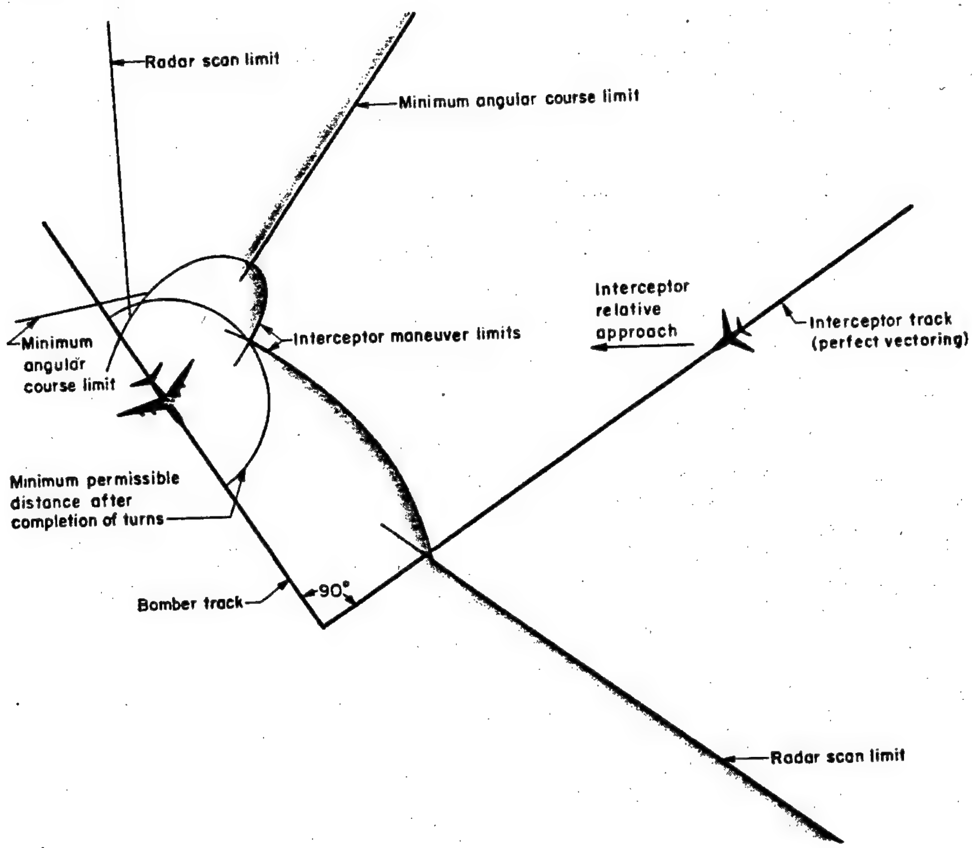

Fig. 47—Conversion barriers, drawn in bomber space coordinates

War II or from recent maneuvers would be unsatisfactory. In this respect the present study differs from previous air defense studies.[17] It may be, for example, that the estimates of AI detection and conversion presented here are too high and should be degraded for pilot error and lack of aggressiveness. Such factors were omitted because of the lack of definite data.

[17] A special study of this subject was made by the Operations Analysis Section, HqUSAF, in October, 1950. Also, the Weapons Systems Evaluation Group completed an interim defense study in January, 1951, on the situation then current.

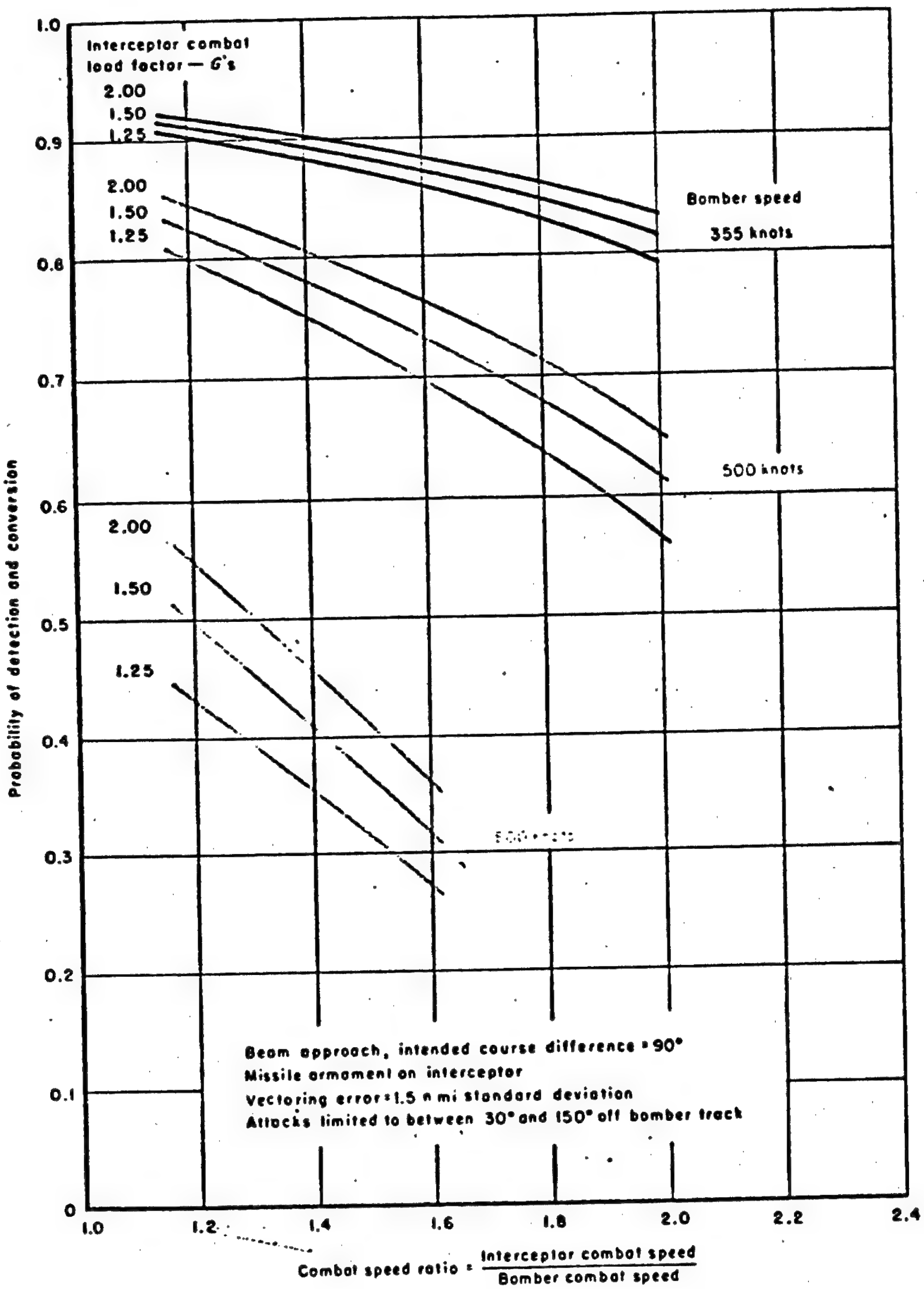

Fig: 48—Probability of detection and conversion

THE DUEL

Types of Damage and Kills

Three types of interceptor kills were considered in the duel.[15] First is the *C* kill, or the type of damage that aborts the attack in progress and all subsequent attacks but leaves the airplane in a flyable condition. The structural vulnerability of interceptors to the 30-mm rounds fired by the bomber is very low. Consequently, it was assumed that the 30-mm rounds could not do sufficient aerodynamic damage to cause the interceptor pilot to lose control of the aircraft. Also, because of the speed advantage of the interceptor over the bomber, and the collision-course tactic, it was assumed that an attack already in progress could be completed with a damaged or inoperative engine and that no lethal fuel fire would occur quickly enough to thwart an attack in progress. Hence, for the *C* kill, the vulnerability of all interceptors was assumed to be roughly the same, because only the pilot and the fire-control system are vulnerable.

The second type of kill is the *A* kill, in which the interceptor will start to fall or to go out of control within 5 minutes after it is hit. This can occur as a result of a lethal fuel fire, a pilot kill, or the killing of the required number of engines. The fighter radar and fire-control gear is not included in *A* damage nor is it considered necessary for a safe return to base.

The third type of fighter kill is the *C′* kill, in which the interceptor will be unable to make subsequent attacks, regardless of its ability to complete the attack in progress. The vulnerable area for the *C′*-type kill was obtained by adding the vulnerable areas of the *A* and *C* kills.

For the bombers, three types of kills were considered: the *K* kill, the *A* kill, and the *C* kill. The *K* kill is an instantaneous kill resulting from major structural damage. The delay-fuzed internal-blast-type missile and rocket armaments are very effective in producing this type of kill. The *A* kill results when the bomber starts to fall or to go out of control within roughly 5 minutes after being hit. The *C* kill results when the bomber, although in flyable condition, is so damaged that it cannot bomb effectively. For the delay-fuzed internal-blast warheads, the vulnerable areas to the *C* kill are the same as those for the *A* kill. For the *K* kill, the vulnerable area is included in the *A* kill. Hence, only

the *A* kill was considered for bombers attacked by interceptors carrying these armaments.

The 30-mm nose-turret high-explosive (HE) rounds and the fragmenting-warhead armaments give both recognizable and unrecognizable kills on the bomber. The unrecognizable kills come from hits on certain of the crew members, the bomb, and bombing equipment. The recognizable kills come from hits on certain other crew members, the engines, fuel, and control cables. With these armaments, the vulnerable areas for the *A*- and *C*-type kills must be determined individually.

Recognition of Kills

Another assumption which affects the outcome of the air battle, particularly at high-attrition levels, concerns the time that it takes the interceptors to recognize which bombers were killed during the course of the air battle. In the air battle study, it was assumed for convenience that all the interceptors involved in the battle would make a first pass at substantially the same time. It was also assumed that, prior to the next pass, all "killed" bombers would withdraw from the battle if the interceptor armament was the 2.75-in. rocket, the MX-904 missile, or projectiles with large VT-fuzed blast-pellet warheads. For the VT-fuzed fragmenting warhead and the 30-mm nose-turret armaments, it was assumed that all "killed" bombers would remain in the battle, because no major structural damage would be done by these armaments and the duration of the air battle would be relatively short. (The definitions of the various classes of kills are used in setting the pattern.) All remaining interceptors would then make a second pass; again, killed bombers would withdraw, and so on.

Weapon Characteristics and the Duel Analysis[10]

The bomber was assumed to have a twin 30-mm-gun tail turret. The characteristics assumed are given in the table on page 147. The 30-mm projectile assumed is a thin-walled, high-capacity HE shell having a delayed-contact fuze. The bomber was assumed always to open fire approximately 8 sec before collision and to fire a 6-sec burst.

Turret Characteristics	TU-4	Stalin	Lenin
Standard deviation of fire-control error, mils	12	10	8
Turret coverage off tail	±70°	±90°	±110°
Radar coverage off tail	±90°	±110°	±180°
Over-all reliability	90%	90%	90%
Rate of fire per gun, rds/min	1,200	1,200	1,200
Maximum burst length, sec	6	6	6
Muzzle velocity, ft/sec	1,800	2,200	2,600
Radar 50% detection range, ft	20,000	30,000	40,000

Five interceptor armaments were studied in detail: the 2.75-in. folding-fin aircraft rocket (FFAR), the MX-904 missile, larger air-to-air missiles having VT-fuzed fragmenting warheads or blast-pellet warheads, larger air-to-air rockets having VT-fuzed fragmenting warheads, and twin 30-mm guns in a nose turret. The missile cases are not strictly duels, since it was assumed that the interceptor would remain beyond the range of the bomber's guns. These five armaments will now be discussed in detail. The assumed availability dates are shown in Fig. 49.

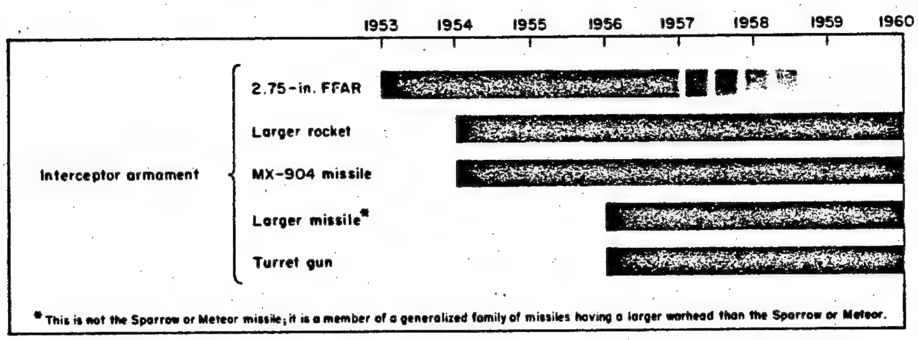

Fig. 49—Availability dates of interceptor armaments

2.75-in. Rockets (FFAR). This armament was considered in both the first- and second-generation interceptors. For the first-generation interceptors (1952–1957), the number of rockets carried was assumed to be 24 or 48 for the F-86D and F-94C, 104 for the F-89D, and 240 for the B-45C. The 48-rocket case for the F-86D and F-94C was included to investigate the effect of armament load and also to investigate the relative merits of multiple-firing passes, since firing appreciably less than 24 rockets per pass does not give a high kill probability per pass.

The characteristics of the 2.75-in. rockets were assumed to be:

Weight	18 lb
Warhead weight and type	1.45 lb; HE contact blast (delayed)
Dispersion (standard deviation)	7 mils
Speed (at burn-out)	2300 ft/sec relative to launching interceptor

Two fire-control systems were considered: the "fixed-time-of-flight" system (like the Avion) and the E-4, or "variable-time-of-flight" system. In both systems the tracking radar obtains the angular rate of the line-of-sight, the range, and the range rate of the target. On the basis of these data and the pre-set rocket time-of-flight, the angle of turn to the desired course is determined. In the system having fixed time-of-flight, the pilot continuously attempts to correct course errors. In the E-4 system, which has a variable time-of-flight, the pilot stops correcting at some point and flies a straight course while the computer continuously determines a corrected rocket time-of-flight and hence the time to fire.

For the fixed-time-of-flight computer, the analysis of the fire-control errors was separated into considerations of the deflection and elevation-prediction accuracies. The errors in the basic input data for the horizontal computer, together with their standard deviations in mils, were calculated to be:

Inaccuracy in interceptor angle-of-sideslip measurement	6 mils
Inaccuracy in radar tracking-of-sight line	4 mils
Pilot tracking inaccuracy	6 mils
Salvo-time inaccuracy	.05 sec
Inaccuracy of rocket time-of-flight (t_f)	.04 t_f
Range inaccuracy at time of release	50 ft
Range-rate inaccuracy at time of release	50 ft/sec
Inaccuracy in the angular velocity of line-of-sight	1.5 mils/sec

Using kinematic and dynamic diagrams of the fire-control problem, together with probability theory, all the foregoing error components can be combined into a statement of the standard deviation of the horizontal fire-control error as a function of bomber speed, interceptor speed, angle between bomber and interceptor space tracks, and rocket time-of-flight.

The errors in elevation of the fire-control system which contribute significantly to the over-all system accuracy are considered to be the mechanization and harmonization errors, the errors in interceptor angle-of-attack measurement, and the errors due to dynamic response effects and tracking inaccuracies. The standard deviations assumed for these errors were, respectively, 4, 6, and 10

mils. These combined to give a 12-mil standard deviation for the elevation-prediction error.

In addition to these random bias errors, the linear standard deviation of the rocket random dispersion was assumed to be 7 mils. Additional error factors were included in considering target evasive maneuvers.

For the E-4, or variable-time-of-flight computer, the errors in the basic input data for the horizontal computer were calculated to be:

Inaccuracy in interceptor angle-of-sideslip measurement	6 mils
Inaccuracy of radar tracking-of-sight line	4 mils
Pilot tracking inaccuracy	2 mils
Salvo-time inaccuracy	.03 sec
Inaccuracy of rocket time-of-flight	.04 t_f sec
Inaccuracy in angular velocity of line-of-sight	4 mils/sec
Range inaccuracy at time of release	50 ft
Range-rate inaccuracy at time of release	50 ft/sec

The random bias errors which were assumed to contribute significantly to the accuracy in elevation include: mechanization and harmonization, 4 mils; errors in angle-of-attack measurement, 6 mils; dynamic-response effects, tracking inaccuracies, and scintillation, 5 mils.

The principal assumptions required for the duel calculations were that

1. The rocket ripple-salvo duration would be 0.4 sec for the "fixed-time-of-flight" system and 0.3 sec for the "variable-time-of-flight" system, the salvo being timed to straddle the exact instant of the desired firing time. The shorter duration for the "variable-time-of-flight" system reflects the desire for a smaller horizontal dispersion to match the smaller fire-control bias errors obtainable with this system.
2. The interceptor would break away immediately after salvo to avoid collision with the bomber. The minimum time to accomplish a breakaway was assumed to be 2 sec. The computer does not tell the interceptor pilot his exact angle off the bomber track and, since even if this angle were known, he would not be able to make last-second adjustments in the weapon's time-of-flight, it was assumed that the same (and the minimum) time-of-flight would be used for all angles off. This minimum time-of-flight is that which would provide a 2-sec interceptor breakaway time in the critical head-on attack.
3. Evasive action, when used, would consist of a sinusoidal motion in the vertical plane with a period of 12 to 18 sec. For the Stalin bomber,

the amplitude of change in altitude would be approximately 2500 ft.

4. The bomber fire would cease at the interceptor salvo time. However, bomber projectiles already launched were taken into account in the analysis of interceptor survival.
5. When the bomber used evasive action, his fire-control system would be ineffective.

The results of bomber duels with rocket-armed interceptors are given in Table 9.

MX-904 and Generalized Air-to-Air Missile. Since it is possible that the MX-904 (Falcon) may become operational during the lifetime of the first-generation interceptors, the F-89D, armed with twelve of these missiles, was considered. This missile was also considered for use with the second-generation interceptors in the later time periods. The characteristics of the MX-904 missile were assumed to be:

Weight	106 lb
Warhead weight and type	7 lb; HE contact blast (delayed)
Speed (at burn-out)	2000 ft/sec relative to interceptor
Maximum range at altitude (40,000 ft)	64,000 ft[20]
Maximum range at sea level	16,000 ft

In addition to the MX-904 missile, two fragmenting (or blast-pellet) warhead missiles were studied in detail: a 400-lb missile with a 70-lb warhead[21] for use against the Stalin bomber and a 600-lb missile with a 140-lb warhead for use against the TU-4 bomber. These missiles were selected from a generalized study[22] as being the optimum sizes for use with the second-generation interceptors. From two to six of the smaller missiles and from one to three of the larger missiles were carried by the interceptor families. The larger missiles all have semi-active radar seekers, VT fuzes, and a speed-at-burn-out of 2300 ft/sec relative to the speed of the launching aircraft. Table 10 presents data on the effectiveness of these missiles at high altitude. Their effectiveness at low altitude is discussed in Chap. 12. Two sets of figures are given in Table 10, one for ideal fuzing and one for intermediate fuzing. These are discussed below.

[20] In the Air Battle Analysis the interceptor, at high altitude, was required to detect the bomber in time to reach firing position at least 30,000 ft from the bomber, and the MX-904's were released from this point.

[21] This missile has characteristics similar to those of the Meteor missile and is somewhat larger than the Sparrow II and III. The Sparrow I missile, since it is a beam rider and has no terminal guidance, is not similar to any missile of the present study.

Table 9

PROBABILITIES OF KILL OF THE NONMANEUVERING AND THE MANEUVERING BOMBER IN A DUEL WITH A ROCKET-ARMED INTERCEPTOR

P_{KN} = probability of kill, nonmaneuvering bomber
P_{KMN} = probability of kill, maneuvering bomber

Bomber	Altitude (ft)	Bomber Speed (ft/sec)	Fighter Speed (ft/sec)	Rocket Time-of-Flight (sec)												
					FIXED-TIME-OF-FLIGHT COMPUTER											
					Number of 2.75-in. FFAR Rockets in Salvo											
					24				54				108			
					P_{KN}		P_{KMN}		P_{KN}		P_{KMN}		P_{KN}		P_{KMN}	
			Attack Sector:		30°–90°	90°–150°	30°–90°	90°–150°	30°–90°	90°–150°	30°–90°	30°–150°	30°–90°	90°–150°	30°–90°	90°–150°
TU-4	2,500	483	724	1.17	.304	.363	....	....	.498	.549	....	....	.690	.704	....	....
TU-4	35,000	600	720	1.20	.245	.201	.120	.118	.427	.340	.215	.210	.612	.499	.340	.340
			900	1.25	.203	.190	.092	.116	.370	.333	.200	.212	.550	.494	.320	.339
			1200	1.32	.151	.168	.087	.101	.285	.297	.168	.190	.437	.456	.270	.311
Stalin	50,000	850	1020	1.32	.252	.157	.162	.135	.453	.305	.309	.272	.693	.438	.505	.437
			1275	1.36	.201	.161	.148	.130	.417	.412	.251	.232	.557	.440	.389	.361
			1700	1.42	.142	.134	.102	.103	.275	.260	.205	.195	.430	.400	.323	.317
					Number of 318-lb Fragmenting Rockets in Salvo*											
					1				2				4			
Stalin	50,000	850	977	1.31	.857	.587	.715	.652	.979	.705	.919	.879	.999	.734	.993	.985
					VARIABLE-TIME-OF-FLIGHT COMPUTER											
					Number of 2.75-in. FFAR Rockets in Salvo											
					24				54				108			
TU-4	2,500	483	724	1.17	.456	.463	....	....	.688	.647	....	....	.860	.769	....	....
TU-4	35,000	600	690	1.19	.398	.349	.136	.150	.620	.536	.248	.271	.809	.685	.385	.417
Stalin	50,000	850	977	1.31	.410	.273	.200	.179	.631	.438	.348	.321	.824	.580	.526	.481
Lenin	50,000	1266	1456	1.44	.164	.161	.090	.122	.313	.293	.180	.228	.487	.431	.295	.363
					Number of 318-lb Fragmenting Rockets in Salvo*											
					1				2				4			
Stalin	50,000	850	977	1.31	.898	.657	.715	.703	.989	.728	.919	.912	1.	.738	.993	.992

* Unlike the 2.75-in. FFAR cases, the fragmenting rocket cases include an appreciable fraction of C kills.

Table 10

HIGH-ALTITUDE KILL PROBABILITIES OF AIR-TO-AIR MISSILES

Intermediate and Ideal Fuzing*

Target	Missile Size and Type†	Altitude (ft)	Kill Probability	
			No Maneuver	1g Evasion
TU-4	GM_{6f}	35,000	.57 (.75)	.48 (.70)
	GM_{4f}	35,000	.35 (.62)	.25 (.50)
	MX-904	35,000	.14‡	.11‡
		35,000	.60**	.50**
	GM_{6p}	35,000	.50	.44
	GM_{4p}	35,000	.31	.26
Stalin	GM_{6f}	50,000	.85 (.85)	.825 (.84)
	GM_{4f}	50,000	.76 (.82)	.70 (.80)
	MX-904	44,000	.15‡	.11‡
		44,000	.62**	.50**
	GM_{6p}	44,000	.59	.55
	GM_{4p}	44,000	.39	.35
Lenin	GM_{6f}	50,000	.66 (.79)	.62 (.77)
	GM_{4f}	50,000	.41 (.65)	.38 (.61)
	MX-904	50,000	.084‡	.064‡
		50,000	.41**	.33**
	GM_{6p}	50,000	.41	.35
	GM_{4p}	50,000	.25	.19

* Figures in parentheses are for ideal fuzing.

† GM = generalized missile. Numerical subscript is approximate weight of missile in hundreds of pounds. Subscript "*f*" denotes fragmenting warhead. Subscript "*p*" denotes blast-pellet warhead.

‡ Single missile.

** Salvo of six.

Fuzing characteristics were found to be most critical in making an evaluation of the effectiveness of fragmenting-warhead armaments. The ideal fuze would be one which would pick the optimum point along the missile trajectory to detonate the warhead for highest kill probability. Unfortunately, this optimum point is a function of the burst pattern of the warhead, the particular path along which the missile approaches the bomber, the magnitude and direction of the miss, the details of the bomber design, etc. At the present time there is no such ideal fuze and none of the development programs expects to produce one. By about 1957 a sharp-angle microwave fuze can be developed having either a fixed time-delay or a variable time-delay which can be set at some definite value by the interceptor pilot before the missile is launched. With such a

fuze there could still be a considerable variation from an optimum burst point as the missile approaches the bomber from various angles. For example, if the missile approached the bomber abeam and at the same altitude, the fuze would probably function on a signal from the wing tip. Similarly, for a head-on attack the fuze would probably be triggered by the nose of the aircraft. On the other hand, in an attack from above or below, the fuze would probably trigger closer in.

In the present study some bounds on the effectiveness of larger-warhead missiles were determined as follows:

1. *An upper bound*, corresponding to the kill effectiveness of a fragmenting warhead with an optimum-time-delay microwave VT fuze in a head-on approach to the bomber from 45° underneath. It was felt that this kill probability would be roughly that obtainable from approaches at other bomber aspects if an ideal fuze existed.
2. *A lower bound*, corresponding to a fixed-time-delay fuze with a blast-pellet warhead which can do major structural damage to any part of the airplane. With this warhead type, a complicated fuze with variable time-delay would not be necessary. Unfortunately, however, the kill probability expected with such warheads would be somewhat lower.
3. *An intermediate estimate*, corresponding to a VT fuze in a fragmenting warhead with a fixed time-delay which is optimum for a random direction of approach to the enemy bomber. An approximate calculation was made of the kill probability obtainable with this fuzing.

Some of the pertinent factors and assumptions in the study of the kill probability associated with these missiles are discussed below.

1. The sources of noise considered which contribute to the miss-distance are glint noise and fading. Glint is the wandering of the apparent center of reflection across the target. It was assumed that this wandering was random in nature and that the root-mean-square value of the excursion from the average center was 20 ft. Fading noise is simply the fluctuation of the amplitude of the echo signal. In seekers which use conical scanning of their antennas, this kind of noise can introduce angular errors. Fading noise was considered only in special cases where the target was maneuvering and the homing-antenna size was small. This effect enters into the computations for the Falcon missile, and the miss-distance data from the Hughes Aircraft Company study of fading was used here. The miss-distances were assumed to have a

circular distribution in a plane normal to and about the line of sight. It was also assumed that the noise amplitude was invariant not only with the angle from which the target was viewed, but also with the target type and size.

2. Target maneuvers were limited to $\pm 1g$.
3. Proportional navigation was used throughout with a navigational constant of four and an over-all missile time-constant of 0.5 sec. The missile dynamics were represented by a first-order system. These parameters were fixed after a study of the effects of noise and maneuver on the navigation problem.
4. The available missile lateral acceleration was limited to $15g$ and the generalized missiles were designed to have a sea-level aerodynamic range of 30,000 ft and were of the integral-boost-glide variety.
5. Mechanical errors in the seeker system, such as static friction and radome distortion, were neglected on the assumption that these effects can be reduced so as to contribute nothing greater to the miss-distance than the effects of noise or of target maneuvers.
6. The dead-time of the seeker was neglected. It is felt that this assumption could be seriously in error and could increase the miss considerably for tail attacks.
7. Launching ranges were required to be greater than 15,000 ft and less than 30,000 ft because of considerations of (1) the time required to correct launching errors, (2) the maximum radar homing ranges consistent with the powers, frequencies, and antenna sizes under consideration, and (3) the required high probability that the missile would not lose the target after launching.
8. Launching errors from a true missile collision course at the end of burning were assumed to be less than 5°.
9. The missile velocity was assumed constant.
10. The effects of electronic countermeasures (ECM) and multiple-target discrimination were not included in the numerical estimates presented in Table 10. Electronic countermeasures were considered in some detail in the study, but it was not found possible to reduce these effects to numerical values. Qualitative conclusions were reached, however, and these are discussed in Chap. 16, Part II. The emphasis of the study was on the designing of defense weapons which would be as nearly invulnerable to ECM as possible rather than on the estimation of

values for ECM degradations. Another study[23] was made concerning design requirements necessary to reduce target-discrimination troubles. This problem is discussed in connection with the surface-to-air missiles described in Chaps. 8 and 9.

11. A reliability of 85 per cent was assumed for all air-to-air missiles as being a desirable level and one which could possibly be reached by the dates that the various missiles in the study were assumed to become operational. Missile reliability has a pronounced effect on the preferred size of the large fragmenting warheads and on missile size. In general, the lower the reliability the smaller the optimum warhead, and the more a salvo of small missiles is favored over a single large missile. A difference in the assumed reliability of different types of missiles could, of course, have some effect on comparisons. However, no great change in the comparison would occur unless the reliability were very low. It is assumed that by 1957 VT fuzes could be almost as reliable as contact fuzes.

The results of the study are highly sensitive to the miss-distance estimates (15 to 20 ft, for the various situations outlined above). Should the miss-distances turn out, in practice, to be smaller than those computed in this study, the *K*-kill values for the small internal-blast warheads would increase to a point where their efficacy in the interceptor-bomber duel would increase more than the unrecognizable kills of the fragmenting warheads. On the other hand, should the accuracy of the missiles be less than that computed, because of ECM, for example, the small internal-blast-warhead effectiveness would degrade rapidly, leaving only the larger fragmenting or blast-pellet warhead missiles as effective weapons.

Larger Air-to-Air Rockets. This armament type was studied in a generalized manner in the same way as the missiles. Since it would probably take considerable time to develop these new rockets, they were only considered for use with the second-generation interceptors in this study. If it is felt desirable, a vigorous development program might produce these rockets for earlier use.

The sizes of rockets used in RAND's study were a 318-lb launching weight with a 165-lb warhead to be used against the Stalin, and a 636-lb launching weight with a 385-lb warhead to be used against the TU-4. The warhead type was

fragmenting (or blast-pellet) and the ballistic properties were taken to be the same as those for the 2.75-in. FFAR. Duel results are shown in Table 9.

Twin 30-mm Gun Nose Turret. The characteristics of the nose-turret guns are listed below:

Fire coverage off interceptor axis	±70° (azimuth)
Radar coverage off interceptor axis	±70° (azimuth)
Gun operability factor	0.90
Rate of fire per gun, rds/min	1200
Maximum burst length per gun	5 sec
Guns	Two 30 mm
Muzzle velocity	1800 ft/sec

It was assumed that the interceptor would open fire 7 sec before collision and that it would fire a 5-sec burst.

The fire-control errors assumed for the turreted interceptor were those given in the CHORE *Final Report.*[24] These are:

	Mils
Bias errors:	
Gun and computer alignment	2
Radar-antenna, gyro, and radome alignment and matching	3
Computer manufacturing tolerances	2
Computer lead prediction, gyro error	2
Computer ballistic prediction, slow-down, yaw, gravity	= functions of present range, angle off, and time-of-flight
Aim Wander:	
Radar aim wander, conical scan	$4.5 + \frac{4}{\text{present range (ft)}}$
Dispersion:	
Gun and turret dispersion	4

The turret weight was determined by analysis and by comparison of the components of the MX-852 turret with those of the turret studied by CHORE. The turret considered for the present study is essentially the CHORE turret with weight provisions for two guns instead of only one 30-mm gun, and with the AN/APG-29 radar replaced by the AN/APG-37.

The results of a duel between the turreted interceptor and the Stalin bomber are given in Table 11.

Table 11

RESULTS OF A DUEL BETWEEN A TURRETED INTERCEPTOR AND A STALIN BOMBER

Collision-Course Attack
50,000-ft Altitude
Interceptor Armament = Two 30-mm guns, 5-sec burst length
Bomber Armament = Two 30-mm guns, 6-sec burst length

Bomber Speed (ft/sec)	Interceptor Speed (ft/sec)	Bomber Kill Probability			
		C Kill* in Attack Sector		*A* Kill† in Attack Sector	
		30°–90°	90°–150°	30°–90°	90°–150°
850	971	.869	.883	.812	.832
850	1458	.870	.860	.830	.782

* *C* kill indicates a state in which the bomber is incapable of effective bombing.

† *A* kill indicates a state in which the bomber crashes or falls out of control within roughly 5 minutes.

It was realized that there are many other possible interceptor armaments, such as fixed forward-firing guns, toss-bombing, ramming, unconventional forms of guns, towed charges, etc., which could have been studied. Forward-firing guns have been studied in the past, both at RAND and elsewhere, and do not appear to be very attractive, compared with the collision-course types of armament, because of the relatively high loss rate incurred in pursuit-course attacks against a defended bomber. The ramming interceptor has been examined briefly. It appears that a very special design of interceptor and associated gear would be needed to do the job effectively and to provide a high survival probability for the pilot. It should be pointed out that optimum surface-to-air area-defense missiles (see Chap. 8) have very large warheads—because of the fact that they *cannot be expected to hit* the bomber. Since many of the missiles considered had as good guidance equipment as the interceptor (or even better), and because of maneuver limitations on the airplane, the problem of obtaining an acceptable ramming hit probability with a manned interceptor is even more difficult. Even under visual conditions the chances of obtaining a hit are small.[25] For these reasons, the ramming interceptor was not considered in detail. Similarly, the hit probability that would be obtained through the use

[25] At Eglin AFB an interceptor pilot tried to pass close under a bomber, head-on, and passed *over* it!

of toss-bombing appears to be small. No novel and impressive interceptor armament was found other than, or superior to, those considered in detail in this chapter.

COMBAT TIME AND AIR BATTLE DURATION TIME

Successive Passes

In studying interceptor tactics it is important to consider whether or not interceptors can make more than one pass on the bombers during a single sortie. This is important because not all interceptors manage to make a successful pass on the first attempt and, more important, there are conditions under which it is economically sound, if successive attacks are permitted, for the interceptor to carry sufficient armament for multiple passes. (See Fig. 41, page 132.) It was felt that multiple passes are feasible and that the air-to-air IFF and control problems associated with this technique can be solved. The results, when each interceptor is allowed only a single pass, can be obtained as a special case from this study.

It is also important to distinguish between successive passes on the same bomber and passes which are made on different bombers, since this affects the duration of the air battle. The optimum load of armament for most cases considered in this study resulted in a high probability that the bomber would be killed on a single armament pass of the interceptor. Also, the AI radar range and scan angle are such that the probability that any given pass attempt would result in a firing pass is high. For these reasons, in a large percentage of the attacks, successive passes would be made on different bombers. For this condition the bomber spacing is quite important in determining the time duration between successive passes.

For bomber spacings up to several miles (as might exist in a cell-type formation), the time between passes is substantially the same as that for repeated passes on the same bomber, hence this case was used for estimation of reattack times in the air battle study. Modifications for other bomber spacings can readily be made.

Calculation of Combat Time and Air Battle Duration Time[26]

The concept of time of the air battle has two interpretations in the Air De-

fense Study. One is the actual or physical elapsed clock time during which the air engagement is in progress; in combination with the bomber speed, this time measures the bomber penetration. The other time is the "combat time" of the air battle and is thought of as the amount of afterburner-on time used by the interceptor in the air battle.

Combat Time (t_{c1}). The combat time for the initial-attack pass was called $t_{\sigma 1}$, which represents the time, in excess of that consumed by a perfectly vectored interceptor, within which 95 per cent of the interceptors that detect a bomber would be capable of completing the attack pass.

Upon reaching the aim point on the first pass, the interceptor was assumed to proceed along the reattack path discussed earlier (page 139) for the second-pass attempt. The minimum time required to traverse this path is denoted by t_2 and corresponds to the ideally vectored interceptor which required zero combat time to make the first pass. Consequently, fuel adequate to provide more than t_2 minutes of combat at the desired combat radius is necessary if an appreciable percentage of interceptors is expected to make a second pass. The additional fuel time, $t_{\sigma 2}$, required by the interceptor who fails to make a first pass and crosses the bomber's path 3 miles from the aim point, was utilized as the extra fuel allowance to ensure that most interceptors complete the reattack path. The combat time required for two pass attempts was assumed to be

$$t_{c1} = t_2 + t_{\sigma 2} \qquad \text{(2 passes)}.$$

For all cases considered, $t_{\sigma 2}$ was greater than $t_{\sigma 1}$; hence, the latter does not appear in the expressions for combat time beyond the first-pass attempt. The combat time for more than two pass attempts was obtained by adding the basic reattack time, t_2, for each additional pass attempt desired. Thus, general expressions for combat time are

$$\begin{aligned} t_{c1} &= t_{\sigma 1} && (D_p = 1), \\ t_{c1} &= (D_p - 1)t_2 + t_{\sigma 2} && (D_p > 1), \end{aligned}$$

where D_p is the design number of passes for which fuel is carried. The design number of fuel passes should always equal or exceed the desired number of ammunition passes so as to provide a reasonably high expectancy that all ammunition loads would be expended before the combat fuel allowance was exhausted. The preferred number of design fuel passes was determined by the Air Battle Analysis as a function of the desired number of ammunition passes.

Air Battle Duration Time (t_{c2}). The air battle duration time, t_{c2}, represents

an estimate of the time a given interceptor would remain in contact with a bomber force and expend his combat fuel allowance. This air battle duration time was derived from the interceptor combat time plus an additional afterburner-off time to allow the interceptor to go from one bomber to another during the air battle. To obtain the time required to acquire and attack another bomber in any specific battle would involve a detailed analysis of the bomber formation and its variation as the battle progressed.

Assuming the bombers to be approximately 3 miles apart, the mean time to attack a new bomber was taken as comparable with that which would be required to reattack the same bomber by starting the reattack 3 miles aft of the bomber. As discussed above, this time is given by $t_2 + t_{\sigma 2}$. To incorporate variations in actual new-attack times about the mean value, it was assumed that the distribution can be further characterized by a standard deviation equal to $\frac{1}{2} t_{\sigma 2}$. Accordingly, the mean time consumed by an interceptor in attempting D attacks on different bombers is, neglecting $t_{\sigma 1}$ which is small compared with t_2,

$$(D-1)(t_2 + t_{\sigma 2}).$$

The time within which about 95 per cent of the interceptors can attempt D attacks is greater than the mean time by an amount equal to or twice the standard deviation of the final-pass attempt, or

$$t_{\sigma 2}\sqrt{D-1}.$$

Taking the time for approximately 95 per cent completion of the last-pass attempts (as a measure of the air battle duration) results in the following expression for air battle duration:

$$t_{c2} = (D-1)(t_2 + t_{\sigma 2}) + t_{\sigma 2}\sqrt{D-1}.$$

This duration, when multiplied by the average bomber speed, gives an indication of the penetration distance covered by the bomber force during the air battle.[27]

Table 12 summarizes the time factors prepared for use in the Air Defense Study.

[27] Limitations of the control capacity of the GCI stations may also add to the duration of an air battle. This is discussed in Chap. 11.

Table 12

AIR BATTLE TIMES

Type	TU-4		TU-4		Stalin		Stalin		Stalin		Stalin		Lenin	
Bomber:														
Speed, knots	286		350		500		500		500		500		750	
Altitude, ft	2,500		35,000		50,000		50,000		50,000		50,000		50,000	
Interceptor:														
Speed, knots	429		402		575		660		675		750		862	
Load factor	1.81		1.4		1.4		1.56		1.6		1.5		1.5	
Interceptor-bomber speed ratio	1.5		1.15		1.15		1.32		1.35		1.725		1.15	
Number of passes \ Time, min	t_{c1}	t_{c2}	t_{c1}	t_{c2}	t_{c1}	t_{c2}	t_{c1}	t_{c2}	t_{c1}	t_{c2}	t_{c1}	t_{c2}	t_{c1}	t_{c2}
1	.53	.53	.83	.83	.52	.52	.35	.35	.31	.31	.13	.13	.28	.28
2	2.7	4.3	6.0	9.5	6.1	8.5	3.0	4.1	3.8	4.8	5.4	6.7	6.5	8.1
3	3.7	7.7	8.6	16.9	9.9	15.7	4.8	7.5	6.5	8.9	9.6	12.6	11.3	15.2
4	4.7	10.9	11.2	24.0	13.6	22.6	6.7	10.9	9.2	13.0	13.7	18.4	16.2	22.2
5	5.7	14.0	13.8	30.9	17.4	29.3	8.5	14.1	11.9	17.0	17.9	24.2	21.1	29.1
6	6.7	17.1	16.4	37.8	21.1	36.0	10.4	17.4	14.7	21.0	22.1	29.9	26.0	35.9
7	7.7	20.1	19.0	42.5	24.8	42.7	12.3	20.6	17.4	25.0	26.2	35.6	30.9	42.7
8	8.7	23.1	21.5	51.2	28.5	49.3	14.2	23.8	20.2	29.0	30.4	41.3	35.7	99.5

t_{c1} = "combat" time, or interceptor afterburner-on time in combat.
t_{c2} = air battle duration, or time interceptor is in contact with bomber force.

AVAILABILITY AND ABORTS

The fraction of the total interceptor force that can be brought to engage the enemy bomber force is a function of many factors. The principal ones are:[28]

1. *The Interceptor Deployment Factor.*

This is the fraction of interceptors that can engage bombers, considering the interceptor speed and combat radius, the geographic location of the interceptor bases, the early warning systems, and the enemy attack strategy.

2. *The Commitment Factors.*

A fraction of the force must be held in reserve because of incomplete knowledge of the situation and the chance of bomber feints. Rules for commitment are generally formulated in standing operating procedures, but in most cases they will be a function of the specific situation and hence subject to the air division commander's evaluation of the situation.

3. *The Availability Factor.*

At any given time, some fraction of the interceptors will not be operational but will be down for maintenance. In addition, there might be fewer pilots than ready aircraft, so that all ready aircraft could not be engaged. In this study it was assumed that *two-thirds* of the interceptors would be available. Also, it was assumed that there would be enough pilots to man all available interceptors. This is in accordance with presently proposed T/O & E's.

4. *Operational Degradation Factors.*

This is a reduction in interceptor effectiveness under operational conditions which results from mistakes on the part of the pilot or ground director, maladjustment of fire-control equipment, etc. Since the equipment considered in this study is more advanced and more nearly automatic than that used in the last war, operational degradation factors derived from that experience cannot be applied directly in the present study.

5. *The Abort Rate.*

Some interceptors will experience an airborne failure of their electronic or mechanical equipment, controls, etc., during the course of the air battle. This effect was assumed to be equivalent to an abort rate, prior to the air battle, of 11 per cent.

The deployment, commitment, and operational degradation factors are not included in the air battle study, because they depend on so many considerations

[28] Factors 1, 2, and 4 are discussed in Part II.

extraneous to that study. These factors are discussed in Part II. The availability and abort rates, however, are included.[29] Of these factors, for a given enemy bomber threat, only the deployment factor is seriously affected by changes in interceptor design characteristics. For the interior of the United States, the only design characteristic which will appreciably influence the deployment factor is the combat radius of the interceptor. As a result, the air battle study alone permits some armament and interceptor-design selections to be made if the comparisons are made at constant combat radius.[30] Such comparisons are given in Figs. 37, 38, and 39 (pages 130 and 131).

VI. Analytical Air Battle Model

The inputs for the analytical air battle model were the result of substudies. These inputs were:

- The ratio of the numbers of interceptors and bombers.
- The probability of detection and conversion.
- The duel results.
- The reattack times.
- Available combat time of the interceptor.
- Number of interceptor ammunition passes.

The outputs of the model were:

- Bomber attrition.
- Interceptor attrition.
- The estimated duration time of the air battle.

The mathematical model employed stressed two features of the physical air battle which are believed to be of predominant importance: the uneven distribution of interceptor attacks over the bombers in the formation, and the continuous withdrawal of damaged interceptors and bombers from the battle while it is still in progress.[31]

[29] In the presentation of the detailed air battle results in Tables 5 through 8 an "index interceptor budget" is used which omits the availability and abort factors.

[30] Since combat radius is dependent on combat time, the combat time must be held constant.

When a large number of bombers is present, the variation in number of attacks received per bomber will approach that corresponding to a random distribution of interceptor attacks over the entire bomber force, each bomber being considered equally likely to be singled out and attacked by a given interceptor. Accordingly, it was assumed that the distribution of attacks is given by a Poisson random distribution. Thus, it is most probable that a bomber would be attacked by a number of interceptors equal to the ratio of the numbers of interceptors and bombers present, although some bombers would be attacked by more, and some by fewer, than this average number.

The periodic withdrawal of interceptors and bombers during the physical battle was approximated in the mathematical model by subdividing the battle into stages; at the end of each stage, the recognizably killed aircraft were withdrawn and the next stage of the battle was fought between the remaining aircraft. Since the interceptor designs of principal interest are those having combat fuel sufficient for several pass attempts, it was convenient to associate each stage with a corresponding interceptor pass attempt. This also relates the time scale of the air battle to the pass attempts. In effect, the model traces the history of the interceptor through the air battle.

Specific assumptions incorporated in, or implied by, the mathematical air battle model included the following:

1. The bomber spacing during the area-defense penetration would be sufficiently large so that an interceptor must be initially vectored against a specific bomber. The probability of detection of a bomber by an interceptor would be independent of the number of bombers or interceptors in the battle area.
2. The bomber spacing during the area-defense penetration would be sufficiently small so that reattacks on the same bomber or on a different bomber need not be differentiated. For spacings up to approximately 3 miles, the times for attack are essentially the same and hence this assumption is valid.
3. The probability of detection and conversion on each reattack would be equal to that obtained on the initial vectored attack.
4. The bomber spacing would be such as to render mutual support fire ineffective.
5. Interceptor attacks upon the same bomber would be staggered sufficiently timewise to enable the bomber to fire a complete burst at each interceptor within the field of fire of the tail turret. (Only a fraction of the interceptor attacks lie within tail-turret coverage; hence, the

time interval between attacks need only average about 1 minute or greater to satisfy this condition.)

6. The supply of bomber tail-turret ammunition would be adequate for all attacks expected during the mission.
7. The possibility that nonlethal damage might accumulate to lethal proportions from successive attacks upon a given bomber was neglected.

The analytical air battle model proceeded from the inputs to the results as follows:

1. The probability of detection and conversion study was combined with the duel analysis to determine the probability that a bomber would survive an attack by a single interceptor.
2. The probability that the bomber would survive a number, *n*, of identical attacks was obtained for the first air battle stage, corresponding to the initial pass attempt by each interceptor.
3. The Poisson distribution formula then gave the probability that any bomber would actually be subjected to *n* attacks in the first stage.
4. The probabilities obtained in (2) and (3) were multiplied and summed over all values of *n* to determine the expected number of bombers killed by all first passes. In an analogous manner, the interceptors lost in the first passes were counted.
5. The process was repeated, using the values of probability of detection and conversion for second passes, a new duel outcome, and a ratio of interceptors to bombers adjusted for the airplanes withdrawing after the first stage, and similarly for subsequent passes or stages.
6. The process ended when the available number of fuel passes, the available armament, or the available penetration distance (converted to combat time) was exhausted.

VII. Conclusions

The results of the Air Battle Analysis, in the form of kill potentials for various combinations of defense weapons and enemy threats, were used as inputs to the synthesis portion of RAND's Air Defense Study. (Figures 37, 38, and 39, pages 130 and 131, show a selection of these results.) When these results were considered in conjunction with the radar network, target-system

geography, and likely enemy tactics, it was possible to arrive at some conclusions on preferred interceptor and armament designs. These conclusions were stated in Chap. 2, pages 43 through 45.

CHAPTER 8
AREA-DEFENSE MISSILES

I. Introduction

If the vehicle that carries a military payload can be made to operate without a pilot, it can be designed for a one-way sortie with considerable economy of construction. It can be made to achieve a high probability of success by being controlled to the point of destruction. Inherently, there is a chance to save manpower. These are all critical items in modern air war, because strength is principally limited by the economic resources and manpower available.

Most scientists and military men agree that guided missiles will some day have a leading role in military operations, but there is a wide disparity of thought as to when that day will arrive. Many of the pieces that make up a guided missile saw service in World War II—AI and H2X radars, servomechanisms for airplane control, and the German unguided V-1 and V-2 missiles were all used operationally. But putting all of these parts together into a missile demands a very high probability that each one will work without supervision. Reliability is thus an important goal in missile design. But reliability is hard to achieve without complete knowledge of the circumstances of failure, and such knowledge can only be gained from a great many cases. Realistic tests of guided missiles are expensive, and therefore not numerous; their very nature usually prevents a complete understanding of the factors involved in failure. These factors, more than any lack of theoretical knowledge, will postpone the day of military reliance on guided-missile weapon systems.

As with any weapon that represents a distinct break with past practice, there is a likelihood that tactics, as well as performance, will be subject to wide variation during an initial learning period. Against this background it was difficult for RAND's defense study to assess the true worth of defensive missiles in any given year. As far as possible, performances were checked by independent analyses. Numerical results were obtained and availability dates were selected to provide some idea of how weapons may compare if everything works as planned, but it is felt that the most important aspects of the missile studies are those which point out critical technical and operational problems, and possible ways of solving them.

This chapter discusses area-defense surface-to-air missiles; these are defined as having ranges of 75 miles or more.[1] Shorter-range missiles are treated as local-defense missiles and are discussed in Chap. 9.

SCOPE

The Air Force has only one program for an area-defense missile having fairly definite design characteristics. This is the Bomarc I program. The missile is estimated to be operational in quantity in 1957 at the earliest, if everything goes well. RAND's study considered this missile and, in addition, made extensive studies of a second, more advanced, missile. This second missile is here called the *generalized area-defense missile*. It was selected from a family of hypothetical missile designs and therefore represents an improved capability.[2] It is estimated that this missile might be operational in 1959, in the same sense as the Bomarc I estimate.

The enemy bomber threats against which the Bomarc I was assumed to be used included the TU-4, the Stalin, and the Lenin bombers (described in Chap. 5). The generalized missile was studied for use against these threats plus that of a Stalin bomber carrying a supersonic air-to-surface missile having a range capability of several hundred miles.

In order to be conservative in the design of the generalized missile, the enemy was given the capability of several tactical "tricks" in the employment of his bombers and air-to-surface missiles, tricks which would act to reduce the effective radius of action of the defense missile.

One such trick was assumed to be a feinting attack by the bomber. Because a missile, unlike an interceptor, cannot be recovered readily once it has been launched, missile defenses may be susceptible to a feinting attack in which bombers approach close enough to cause the missile to be launched and then turn around and try to get to the maximum missile range before the missile, thus causing the missile to be wasted. To be fully protected against this maneuver, the defense missile must be held back and launched only after the enemy target is so close that it can be caught even if it turns around. In this event, if the target holds to its original course, the missile will reach the target

at a range much less than maximum missile range. This reduced range is called the protected or defended radius. The ratio of protected radius to missile design range[3] depends on the relative speed of the missile and target airplane, target maneuverability, etc., but in general is of the order of 1:2 to 1:3.

Another tactic credited to the enemy would be that of withholding the launching of offensive air-to-surface missiles until defense missiles had been launched and assigned to attack the bombers and were well on their way. This would force the launching of a second salvo of defense missiles to cope with the air-to-surface missiles. This second salvo would reach the missile targets much closer to the defended area than the first salvo, thus reducing the "protected radius" for these weapons still further. This tactic is unpleasant for the bomber crews and might not even be effective if the seeker can be designed to switch from the bomber to the air-to-surface missile when the air-to-surface missile is launched. However, the tactic was considered in establishing the required defense-missile range capability in order to be conservative in designing the defense system.

As in the interceptor study, it was assumed that the attacking bombers might come over under good or bad visibility conditions, in various formation designs, etc. However, in the missile case, the guidance and homing were assumed always to be done electronically and the bombers were assumed to be incapable of defensive fire or mutual protection except in one respect: the bombers might attempt to fly in such a formation as to make it difficult for the missile seeker to operate entirely with the signals from only one target. This is the "multiple-target resolution problem." The missile seeker can be redesigned to surmount this problem by separating the targets by radial-velocity discrimination or by having a sufficiently sharp beam, together with high missile load factor, to separate targets at any spacing soon enough during approach to home effectively on one of them, or by a combination of these. In the generalized-area-defense-missile study this requirement for target resolution was imposed on the missile design.

Bomber attacks were considered at various alitudes, including the low altitudes of 1500 ft at night and 200 ft in daytime used in the interceptor study. It would be desirable to obtain such low-altitude performance from the area-defense missile, but it is realized that this is extremely difficult and is not expected to be achieved by the Bomarc I. These detailed studies of possible

[3] Except where specifically stated, "missile range" refers to "missile design range" in Chaps. 8 and 9.

enemy tactical tricks (and several electronic countermeasures studies) were made to see if missiles could be "intelligent" enough to circumvent foreseeable difficulties, since this lack of intelligence and judgment is one of the criticisms leveled against the guided-missile concept.

II. The Bomarc I

The major part of this chapter is devoted to the generalized (1959) area-defense missile, but first the assumpions relative to the performance and effectiveness of the Bomarc I will be presented.[4]

The properties of the Bomarc I, as presently planned, are understood to be:

Range	100 miles
Speed	Mach 2
Powerplant type (mid-course flight)	Ramjet + liquid rocket boost
Take-off weight	10,900 lb
Warhead weight	300 lb
Warhead type	Fragmenting
Warhead kill probability	0.75 against aircraft
Normal load factor	$\pm 7g$
Seeker transmitter average power	250 watts
Seeker transmitter wavelength	X-band
Seeker antenna diameter	24 in.

The missile weight given above and the cost given below were independently estimated from the other design specifications. The contractor's results were studied and confirmed.

By the methods discussed later in connection with the generalized area-defense missile, the manufacturing cost of the Bomarc I was estimated to be $32,000 and the effective annual cost per operational missile (including all supporting men and equipment) was estimated to be $61,700.

The planned seeker design is expected to give the Bomarc I no low-altitude capability and no capability against *small* vehicles such as missiles. In addition, the Bomarc I powerplant and aerodynamics limit its maximum operating altitude to 60,000 ft.

III. Generalized Area-Defense Missile

MISSILE REQUIREMENTS AND ASSUMPTIONS OF THE STUDY

The deficiencies of the Bomarc I suggest the principal new features that an advanced-design area-defense missile should incorporate. These are principally the ability to cope with supersonic air-to-surface missile threats and low-altitude targets. Against the first of these, the generalized missile was allowed (as will be discussed later) seeker range performance, missile maneuverability, and ground-radar vectoring accuracy to a capability as high as would seem to be feasible by 1959. As a result, a capability against missiles traveling at a Mach number of 3 to 4 at altitudes up to 120,000 ft was assumed. Since the capability of a defense missile against the offensive missile falls off sharply above that altitude and speed, it is felt that a different type of defense against the more advanced type of attacking missiles (such as intercontinental ballistic and glide rockets) will be required. This matter is being studied further by RAND.

In seeking a low-altitude missile capability (against attacks at 200 ft in daytime or 1500 ft at night) two difficult problems arise; these are:

- To obtain a satisfactory low-altitude *detection* network capable of continuously tracking enemy bombers and *controlling* the defense missile with a high degree of accuracy and minimum time-delays.
- To design a radar[5] target seeker which can lock on the desired target and discriminate against large ground-clutter signals and possible reflections of the target signal or other distortions of the radar beam caused by the ground.

These problems are considered more difficult than the aerodynamic and control problems of achieving high- and low-altitude effectiveness. Some of the problems of low-altitude ground-radar and seeker design are discussed in this chapter and some possible development directions are indicated.

Some assumptions were made concerning the tactics by which the missiles would inflict attrition on the attacking bombers. These assumptions concern:

- Uniformity of the distribution of missiles among the bombers attacked.
- Recognition (or nonrecognition) of bomber kills during the engagement.

[5] There may be some possibility of the use of infrared, etc., but the radar approach was the only one considered in detail in the present study.

- Number of separate missile salvos fired during the engagement.

It was assumed that the assignment of missiles to bombers would be at random. It is felt that nothing better than random assignment can be expected with presently envisaged radar target-seeker designs and assignment techniques. The type of warhead assumed for these missiles (blast pellets against manned bombers, plus fragments to kill the bomb in air-to-surface missiles) would give a quickly recognized kill against manned bombers. Some calculations have been made of the effectiveness of area-defense missiles when two salvos and recognition of killed bombers between salvos were assumed. However, the principal evaluation of the area-defense-missile system was made on the assumption that no kills would be recognized (detected or determined) and that therefore only one salvo of missiles would be fired.

The requirements that the missile be able to cope with high-speed missiles and low-altitude targets being kept in mind, the principal effort of the study was then centered on the evaluation of a large family of hypothetical defense missiles characterized by various ranges, warhead sizes and types, seeker powers, antenna-dish sizes and types, maneuverability capabilities, etc. The criterion for the selection of the best combination of design parameters was least over-all defense-system cost. A brief discussion of the assumptions and reasoning leading to the choice of preferred values for these parameters is presented below.

Under the tactical assumptions described above, all the parameters of missile design, except missile range, can be chosen by determining the least value of

$$\frac{\text{effective annual cost per operational missile}}{\text{(probability of acquisition and conversion) (probability of kill)}}.$$

In many cases in which missile-system parameters might have been chosen by calculations employing this criterion,[6] judgment had to suffice for lack of time. This was the case, for example, in making a choice of the ground-radar environment.

GROUND-RADAR AND MID-COURSE GUIDANCE

The ground radars associated with the first-generation area-defense missile, the Bomarc I, will probably be the AN/CPS-6B and AN/FPS-3 radars. For

[6] The probability of acquisition and conversion is separated from the probability of kill according to the following definition: Probability of acquisition and conversion is the probability that the seeker can acquire the target and direct the missile onto a collision course with it. The probability of kill is the probability that a missile starting on a collision course kills the target. This latter quantity is therefore usually defined by the warhead characteristics and the miss-distance, which in turn is affected by missile maneuverability and target glint.

the second-generation missile, to which the generalized-missile studies apply, the ground-radar system might also be a generation later and be the AN/FPS-7 or Volir radar, or some other development not clearly foreseen at present.[7] In addition to, or instead of, these radars, which provide only high-altitude coverage, it is hoped that there will be adequate low-altitude radar coverage. This may well be achieved by radars of the Muldar type, discussed in Chap. 12. These later radars are visualized as being of short range and quite closely spaced (say, 40 miles apart). Thus, the range of the area-defense missile could be much greater than the range of any one radar. Data concerning the enemy attacker and defending missile positions would have to be passed from radar to radar or collected at centrally located data-handling facilities covering an area comparable with that within the missile radius. This probably means that the radar spacings and ranges have no influence on the desirable missile range.

If the area-defense-missile electronic components are not sufficiently developed to have a low-altitude capability, the missile can use the data of large radars such as the AN/FPS-7. In this case, it might well turn out to be advantageous to tailor the missile range to the range of such a radar to minimize the data-passing problems. In either event, it is visualized that both targets and defense missiles will be followed by track-while-scan equipment attached to the search radars and that intercept computers will be used to effect an interception. The vectoring, or mid-course, error was estimated by the same procedure as that used for the interceptor. That is, the errors in the positions of the target and the defense missile were estimated from the design characteristics of the radar and track-while-scan channel. These errors were all converted into an equivalent error in lateral displacement of the defense-missile and target courses. If the target was a manned bomber, the resultant error was assumed to be Gaussian in distribution and to have a standard deviation of 1.4 miles. (This allowed for radar resolution difficulties.) In the case of missile targets, the vectoring error was assumed to be about 3750 ft standard deviation, this being typical of what is expected for the AN/CPS-6B, AN/FPS-3, or AN/FPS-7 plus track-while-scan units. A value of $\sigma = 3000$ ft might be typical of the Muldar radar system, although it could be designed for other accuracies. The value of $\sigma = 3750$ ft was taken to be applicable to the generalized area-defense missile in 1959.

MISSILE TERMINAL GUIDANCE

The problems studied in connection with missile-seeker design were:

- The choice of an active or semi-active type of radar target seeker.
- The determination of the probability of acquisition and conversion and of how it is affected by some of the same factors that affect missile performance.
- The seeker design requirements to ensure that closely spaced multiple targets could be resolved soon enough to permit successful homing on one of them.
- The elimination of ground-clutter signals, echoes from rain clouds, etc., so that the seeker will function at low altitudes. This must be accomplished with no serious increase in seeker acquisition time.
- The expected miss-distance of the missile, as determined by the fundamental glint limitation if the preceding problems are solved.

These problems are now considered in turn for the generalized area-defense missile.

Seeker Type

If active radar target seekers are used, each missile must carry a radar transmitter. This will result in increased missile cost. If the semi-active system is used, the missile can be smaller, but the cost of ground illuminators must be added. If the missile is restricted to high altitudes, high-power tracking radars might be used as illuminators by locating them near the missile launchers and ground search-radar sites. The costs of these two approaches are comparable. However, if low-altitude capability is to be achieved, illuminators will be required in very large numbers and will have to be spaced every few miles over the defended area. This would be much more expensive than the active-seeker case, so in the present study it was decided to design the area-defense missile around an active seeker.

Acquisition and Conversion

The two principal features of seeker design that influence the system effectiveness through both the missile cost and the probability of acquisition and conversion are antenna-dish size and average power (related directly to seeker weight). An important missile design parameter which affects both the missile

cost and the probability of acquisition and conversion is the missile's normal load factor or aerodynamic limits, a measure of missile maneuverability. The probability of acquisition and conversion is also greatly affected by the scan angle and the mid-course guidance error, hereafter called vectoring error. The method used to determine the probability of acquisition and conversion is described below. This probability can then be combined with the missile cost, according to the system effectiveness criterion discussed earlier, to determine the optimum missile-system parameters. (See "Missile Design and Performance," page 181.)

1. The missile maneuver barrier, shown in Fig. 50, was obtained by plotting the minimum acquisition range for conversion as a function of vectoring error. The determination of this locus took into account a missile response lag of 1 sec, a terminal smoothing time of 1.3 sec, and a maximum lateral load factor determined from the missile's shape, weight, altitude, and speed.

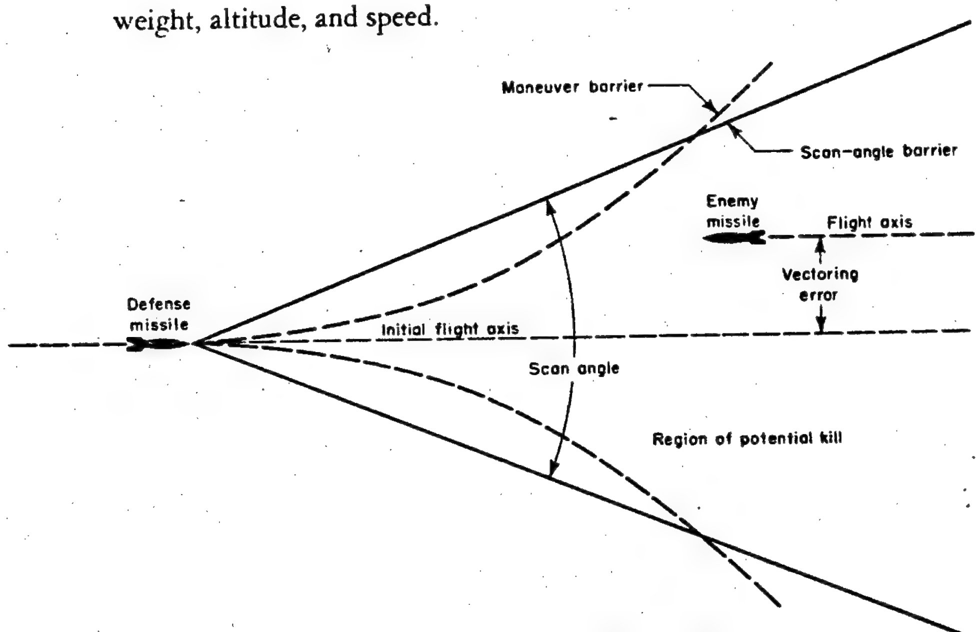

Fig. 50—Schematic of interception barriers

2. As previously noted, the Gaussian vectoring error was characterized by a standard deviation of 3750 ft. The error distance, within which about 95 per cent of the targets will be observed, was then determined. The sight angle was obtained by using nominal values for missile

velocity, target velocity, altitude, missile load factor, and the range from the missile. The sight angle was defined by the range and the intersection of the maneuver barrier with the 95 per cent point on the vectoring-error distribution curve. The seeker was then considered to have a scan angle of approximately the resulting amount, namely 20°, which was held constant for the rest of the calculation. A further important quantity, the scanning time, was also assumed to be semi-invariant. To take maximum advantage of the radar information rate, so that changes in beamwidth within a fixed scan angle would not seriously affect the power requirement obtained by calculations, the scan time was adjusted to be essentially the same as the over-all missile-response time, i.e., about 1 sec.

3. A probability density function of radar detection and acquisition was constructed as a function of the seeker parameters of importance, e.g., power, antenna size, etc. The product of this function and the conditional probability density function representing possible target positions, summed over all locations from the instant of seeker turn-on and within the scan-angle and maneuver-barrier limits, produced a single number representing the expected probability of successful target acquisition and conversion.
4. The process of target acquisition by the missile seeker is considered to consist of two distinct phases: The first is the search phase, wherein (for example) the seeker scans the antenna beam through the scan angle and detects the presence of a target blip in some single scan; after this occurs, the search phase is stopped and the seeker is effectively returned to the position of the original response, at which time a second blip must be observed without delay. This sequence of operations is required by the high closing velocity of the missile and the target. It is the accumulated probability of the successful completion of this sequence that is defined as the probability of acquisition.
5. The range performance of the radar target seeker was studied assuming the echoing area (fluctuating) for a missile target to be 1 m² and the seeker to be designed to make maximum use of known techniques for keeping the transmitter power requirements down. This results in a complex seeker design and requires a transmitter power near the maximum presently available. The actual power needed depends, among other things, on the assumed losses in the system and on any degrada-

tion occurring in field-operation performance because of improper maintenance. The field maintenance degradation was here assumed to be about 8 db, which is slightly better than typical World War II radar maintenance performance. Miscellaneous systems losses were assumed to be about 9 db. These reflect an expectation that improved design and maintenance procedures will exist by 1959.

6. Representative curves indicating acquisition probabilities for various values of total power losses for a transmitter average-power output of 430 watts are shown in Fig. 51. The derivative of the curve for 17-db losses is the density function required.

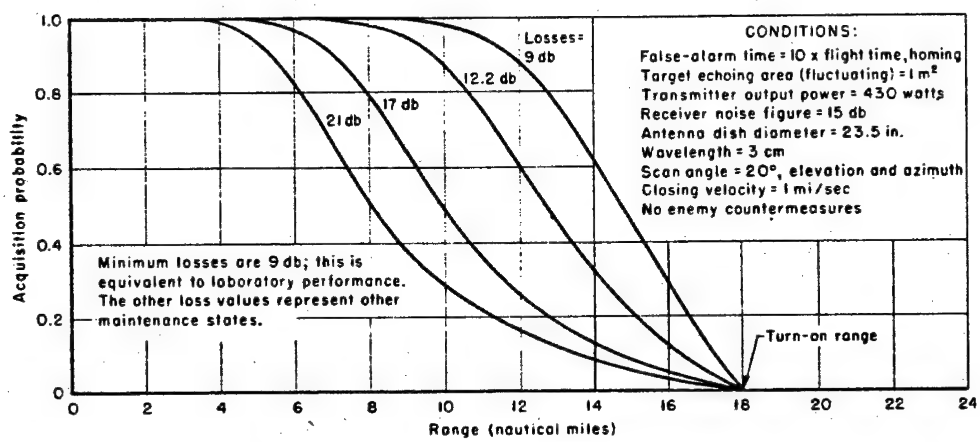

Fig. 51—Probability of acquisition (lock-on) vs range for several maintenance states, an active-seeker system and cumulative two-blip detection criterion

Seeker Resolution

In principle, multiple targets can be resolved by one or more of the following means: range discrimination, angle discrimination, and velocity discrimination. In a conventional pulse seeker, such as is now visualized in the Bomarc program, a combination of range and angle discrimination can be used effectively. There must exist a certain relationship between the seeker beamwidth, the missile's normal load factor, missile and target speeds, etc., to meet this requirement. A study of this question indicated that for missile and target speeds of 3000 ft/sec, for a 15*g* normal load factor, and for a 24-in. antenna at X-band radar frequency (which is one case of interest in the present generalized-missile study), the angular resolution is sufficient to avoid any multiple-target problems for any bomber spacing. If velocity tracking is employed on the seeker,

using doppler-frequency shifts, there will be a multiple-target resolution effectiveness, thereby making it unnecessary to obtain angular discrimination and thus removing the wavelength restrictions, etc. This type of seeker was also considered in the present study.

Clutter Elimination

The low-altitude ground-clutter-elimination problem has been studied in connection with the generalized-area-defense-missile seeker. It has also been studied in connection with the air-to-air-missile seeker, the interceptor's AI radar, Muldar radar, airborne early warning radar, etc. These difficulties are discussed in Chap. 12. The studies of this problem have not gone far enough to determine the detailed design of the seeker needed to accomplish low-altitude area defense. However, they do indicate some avenues for development effort.

Miss-Distance

If mid-course guidance errors have been corrected, and multiple targets have been successfully resolved, the miss-distance will depend solely on guidance and control during homing. The principal factors causing a miss are target maneuver and target glint. Calculations previously cited (in Chap. 7) for the air-to-air missile-homing studies[8] were used. A root-mean-square miss-distance of 20 ft was assumed to be the measurement of performance of surface-to-air missiles. The conditions, assumptions, etc., used in the study were essentially the same as those given above (page 153), except that surface-to-air missile attacks were assumed to come from the forward quarter, whereas the air-to-air attacks were assumed to be abeam. This 20-ft miss is associated with the 15g acceleration limit of the defense missile and a 1g target maneuver.

MISSILE MANUFACTURING COSTS

Studies of missile manufacturing costs were made by estimating the direct man-hours required to make the component parts; these costs were expressed in dollars, with allowances for indirect labor, material cost, overhead, and profit. In general, the RAND estimates of missile costs were in fairly good agreement with those obtained by General Electric, Boeing, and the Army Operations Research Office. A detailed cost breakdown and methodology is presented else-

where.[9] The numerical costing results for the preferred missile designs, as a function of range, are given below.

MISSILE LAUNCHING COSTS

These costs are defined as the total cost of maintaining ready missiles in the field and include the missile manufacturing costs.

The area-defense group[10] considered in this study is sufficiently general in nature to employ either the Bomarc I or the generalized area-defense missiles. The group is not deployed about any particular target but is strategically located for the defense of a given area. Each of nine launching sections incorporated in the area-defense group maintains 40 missiles in a ready condition, and an additional 40 missiles in reserve. To minimize the annual costs, the ready missiles are vertically mounted on platform-type launchers and are maintained in the field.[11] This disposition is intended to minimize the necessity for four shifts of personnel and to provide a ready defense at any given time.

The area-defense group operates from a semi-permanent-type installation and has personnel appropriate for the operational and support functions. Only the launching function and its associated costs are considered here. Guidance costs are discussed in Chap. 11.

Launching costs include the cost of the installation, missiles (including practice firings and spares), communications, fire-control and testing panels, organizational equipment, launchers, and handling equipment, as well as the cost of initial and annual spares, transportation, pay and allowances, training, travel, services and miscellaneous, overhead, and intermediate commands. By a detailed consideration of the maintenance and operational requirements, as well as of the support personnel needed, the personnel requirements and equipment costs shown in the table on page 180 are estimated to be required for 40 operational missiles.

In summary, the launching cost per missile was found to be relatively independent of the number of missiles required for the defense levels considered. It may be expressed as the sum of two terms: one term is directly proportional

[10] "Group" is used here to mean a hypothetical military unit, roughly the size of an Air Force group, designed specifically for handling certain defense missiles.

[11] This demands serious development work in the designing of a missile and in the procedure for its maintenance, particularly of its power system, so that it will be capable of standing in a ready condition in the field for periods of time up to 6 months.

Personnel

Operational functions:	
Officers	5
Missile testing	16
Assembly and repair	26
Operations	19
Total number	66
Support functions:	
Officers	5
Security	10
Fire protection	5
Transport	7
Food service	11
Supply	5
Maintenance	10
Medical	4
Headquarters and miscellaneous	8
Total number	65

Equipment Costs

Item	*Number Required per Section*	*Unit Cost*
Launchers	40	$ 1,000
Fire-control and test panels	1	150,000
Communications and associated equipment	1	50,000
Missile-handling equipment	1	110,000
Organizational equipment	1	185,000

to the missile manufacturing cost, and the other is a constant. The first term results from the purchase of all defense missiles, i.e., those used for the actual operation, as reserves, as spares, and for practice firing. The second term results from the cost of equipment, personnel, and facilities. By assuming the average life of a weapon system to be 4 years, the effective annual cost per operational missile for the generalized area defense may be approximated as 0.962 times the missile manufacturing cost plus $27,000. These costs are discussed in more detail elsewhere.[12] For the particular design derived in the discussion that follows, these costs are given in Fig. 55 (page 185).

MISSILE DESIGN AND PERFORMANCE

This section describes the choice of missile design factors, such as configuration, powerplant type, seeker-dish size, maneuverability, etc. Corresponding to these design features, there is a best flight pattern for any range; this pattern will also be described.

In the design study, the range of the missile was considered to be its maximum aerodynamic range. In actual operation, this might exceed its tactically useful range (the "protected radius" mentioned earlier) because of the possibility of a feinting attack by enemy bombers or because air-to-surface missiles might be released by the bombers after the first salvo of defense missiles has been launched. The relation between missile design range and the protected radius is shown in Fig. 52.

Because of the premium placed on high speed to catch a feinting target, only supersonic ramjet and rocket missiles were studied. Since an area-defense mis-

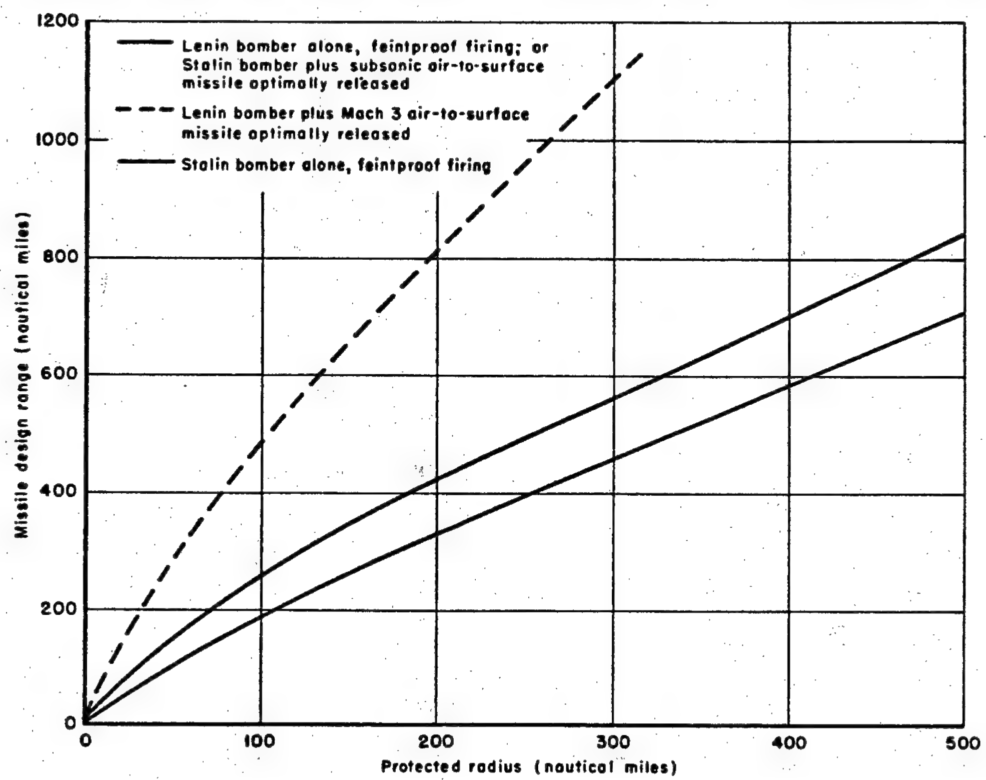

Fig. 52—Design range required vs protected radius: generalized area-defense missile

sile must fly an optimum-performance trajectory for the major portion of its flight, much of the information developed in RAND's long-range rocket and ramjet studies[13] could be used here. These studies indicated that the manufacturing cost of glide rockets and ramjets for a given range[14] was about the same. In order to pick a specific case, and since it was felt that rockets were likely to be more useful than ramjets above a 100.000-ft altitude, detailed surface-to-air rocket systems were studied. The detailed rocket studies discussed in the following pages were compared with contractors' studies of ramjets, with the result that the findings for surface-to-surface missiles were confirmed for surface-to-air missiles if the attack altitude was equal to or less than the cruise altitude of the ramjet; i.e., the cost of a rocket system is less than that of a ramjet if the attack altitudes are substantially higher than the ramjet cruise altitude.

Investigation showed that one-stage rocket power is better than two-stage power up to a 500-mile range. Detailed performance studies were therefore made for two cases: (1) a missile having one stage of burning, which jettisons its powerplant at the end of burning; and (2) an integral one-stage rocket. It was found that the cost of the former was generally less. However, if designed for attack below 60,000 ft, they cost essentially the same. The generalized missile discussed below is one that would be capable of jettisoning its powerplant. The comparative investigation of one- and two-stage rockets, and the detailed assumptions and calculations of flight mechanics, propulsion, structures, aerodynamics, and manufacturing costs required to determine the proper design of the missile, are discussed elsewhere.[15] A few remarks may be made here, however.

The missile is vertically launched with an initial axial load factor of 1.5*g*; from its launching point it travels in a gravity turn to a maximum altitude at which its lift equals its weight and its lift/drag is at a maximum. At approximately this point it reaches maximum velocity and the rocket burning ceases. It then coasts in a maximum lift/drag glide to some point about 50 miles from its target, at which point it is navigated by ground-radar data via command guid-

[14] In a tactical situation, it is really more appropriate to compare rockets and ramjets at the same protected radius. Since the present study requires that the missile catch a target which begins a feint just as the missile is released, this faster missile would require less range. For instance, if the protected radius is 300 miles, a rocket missile would require approximately a 500-mile range to catch a feinting Stalin aircraft, whereas a ramjet would require an 800-mile range.

ance and then via the missile-borne homing radar to its target. The conservative calculations in flight mechanics were based on a negative vertical turn of 1g followed by a positive 2g turn leveling out at target altitude for the approach. The missile configuration is that of fixed monoplane wings with cruciform movable tails. The wings are triangular and the body is a cone plus cylinder with boattail. The missile is of semimonocoque construction, having SAE 4130 steel skin and a radome nose constructed of a ceramic sandwich material. The single jettisonable powerplant uses gasoline (JP-3 jet fuel) and white fuming nitric acid. The motor is gimbaled to provide attitude control during powered boost. Control is achieved by movable aerodynamic fins during the coasting flight. The low-altitude-capability problem, in addition to placing severe requirements on the ground radar and seeker, demands that the mid-course tracking system tell the missile to arrive at a low altitude but to travel at that altitude for a very short time to avoid severe slowdown due to high drag.

Detailed performance studies consisted of calculating, for various ranges and warhead sizes, the propellant-to-gross-weight ratio required for various values of wing sizes and body diameters, for values of normal load in the homing turn, and for various radar seeker weight, size, and power requirements. The missile structure was designed for normal loads of 15g, because, for this capability, the effect on missile kill probability of the target maneuver considered is small.

The principal optimizations were seeker power, seeker-dish size, and wing size for various altitudes and ranges. These optimizations were accomplished by looking for those values of the parameters which would minimize the value of

$$\frac{\text{effective annual cost per operational missile}}{\text{probability of acquisition and conversion}}.$$

In addition, some parameters (such as wing size and number of rocket power stages) were affected by the flight economy over the ascent and mid-course path. The results of these optimizations for a typical 450-mile missile, having a 750-lb warhead and designed for a 100,000-ft-altitude attack capability, are given by the missile description in Table 13 (page 186). A sketch of the missile is shown in Fig. 53. Manufacturing costs of missiles of other ranges and payloads were obtained as shown in Fig. 54. Effective annual costs per operational missile for the same designs are shown in Fig. 55.

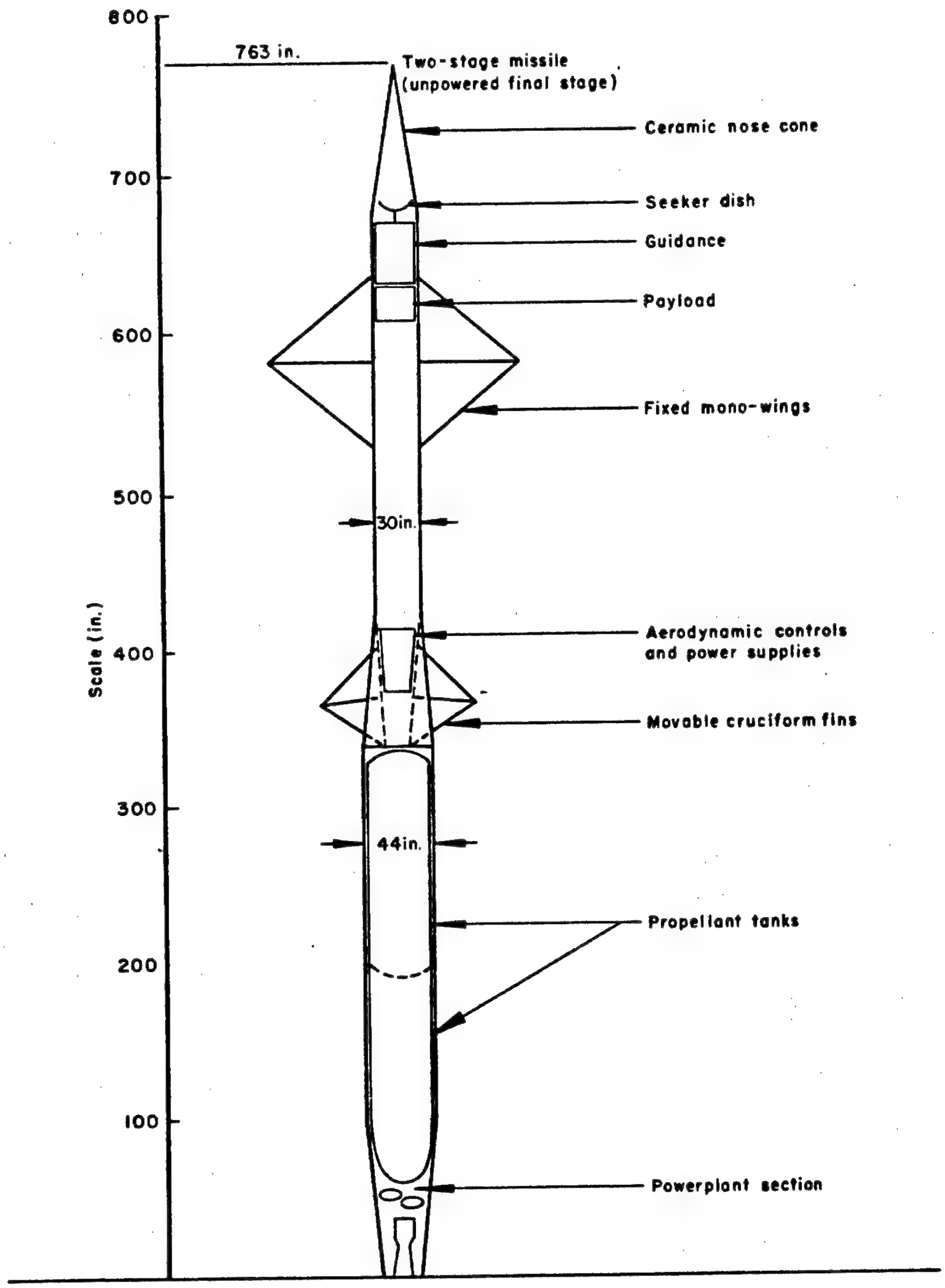

Fig. 53—Generalized area-defense surface-to-air missile—450-nautical-mile range

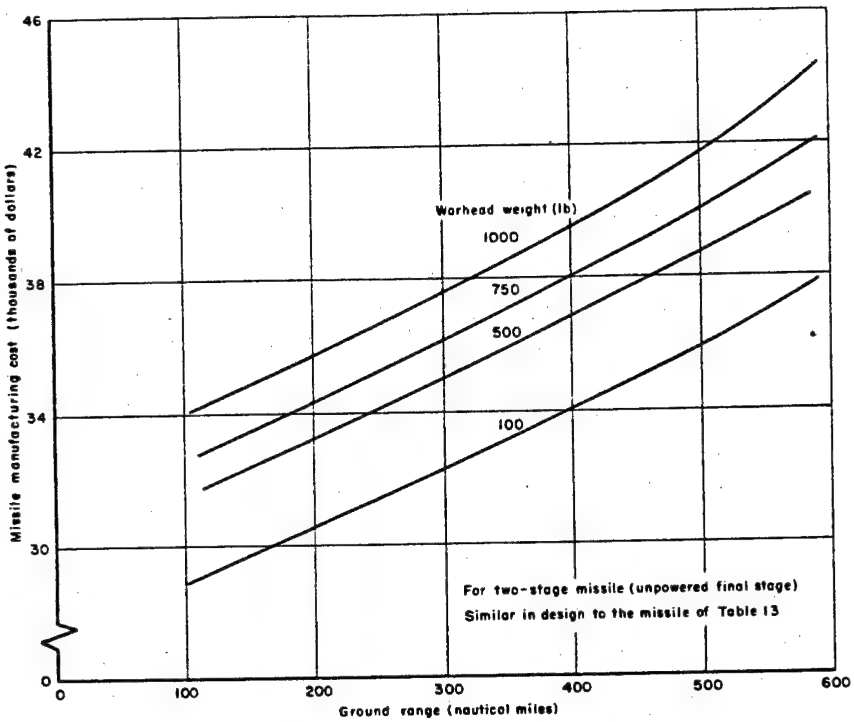

Fig. 54—Area-defense missile manufacturing cost vs range

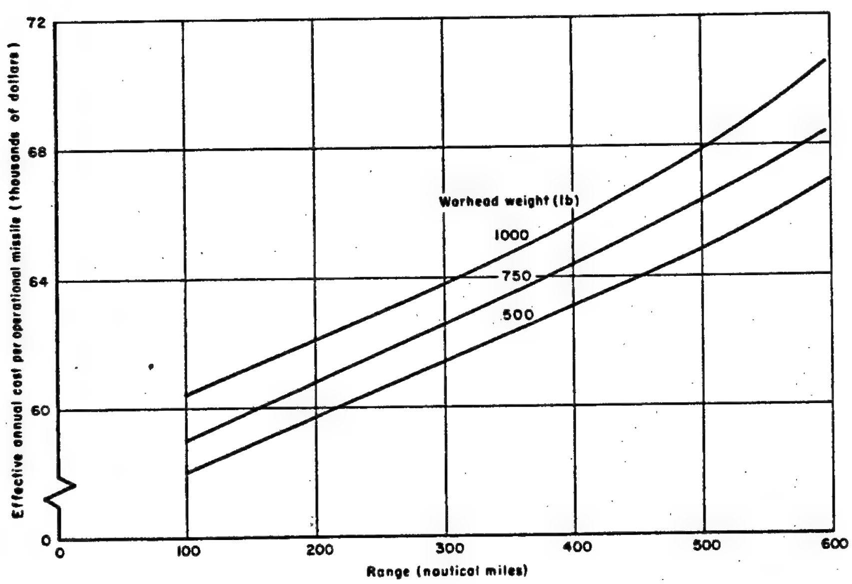

Fig. 55—Effective annual cost per operational missile vs range

Table 13

GENERALIZED SURFACE-TO-AIR MISSILE FOR AREA DEFENSE

Enemy threat: Mach 1.3 bombers and Mach 3 air-to-surface missiles

Warhead	Dual-purpose fragment and explosive pellet, 750 lb
Range	450 nautical miles to terminating altitude of 50,000 ft and velocity of 2000 ft/sec
Rocket power	Two stages: booster (liquid rocket) with unpowered final stage
Missile configuration	Fixed mono-wing (triangular planform) with movable cruciform tail
Glide altitude	100,000 to 70,000 ft
Glide Mach number	6.5 to 3.0
Gross weight	21,700 lb
Estimated manufacturing cost	\$38,900
Over-all length	63.6 ft
Wing span	13.6 ft
Diameter	Booster, 44 in.; final stage, 30 in.
Ratio of wing area to body cross-sectional area	10
Radar seeker	Active type; average power, 430 watts
Seeker-dish diameter	23.5 in.
Normal load factor	15g
Propulsion	Single-thrust liquid rocket, 32,600 lb

Figure 56 shows the manner in which

$$\frac{\text{effective annual cost per operational missile}}{\text{probability of acquisition and conversion}}$$

increases with altitude, each point on the graph representing an optimized missile. For comparison, an integral one-stage missile is shown. A ramjet missile's performance is estimated to lie about halfway between these curves. An important point shown in Fig. 56 is that a two-stage rocket missile maneuvering with aerodynamic surfaces would be effective even up to an altitude of 115,000 ft. At some higher altitude, lateral rockets would be more effective than wings and fins, but this crossover altitude has not yet been determined. Figure 57 shows the effect of body diameter (related directly to dish size) on

$$\frac{\text{effective annual cost per operational missile}}{\text{probability of acquisition and conversion}},$$

a consideration leading to the choice of the body diameter in Table 13.[16]

The selection of all missile-design parameters, except warhead type and size

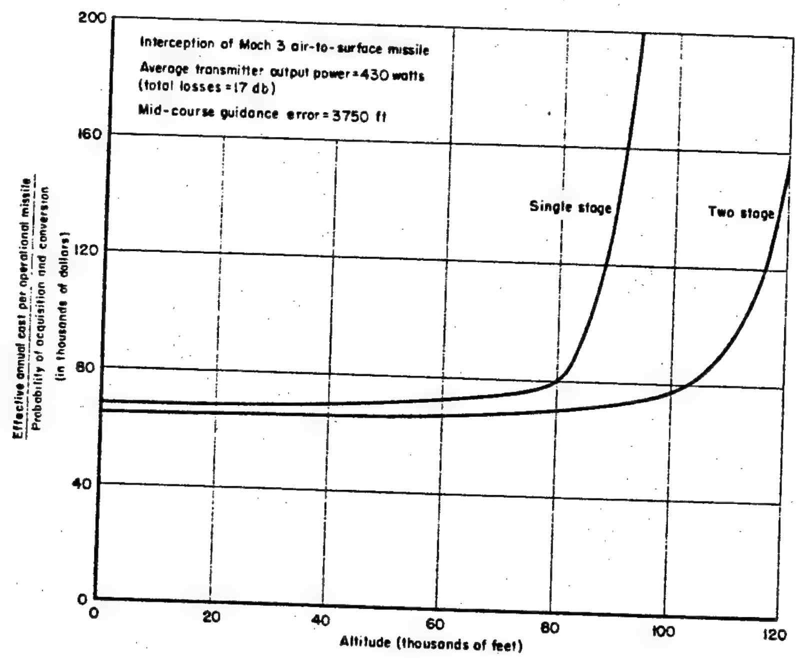

Fig. 56—Cost quotient vs altitude

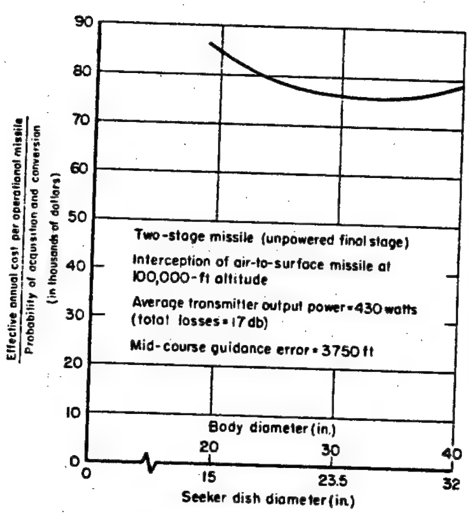

Fig. 57—Cost quotient vs body diameter

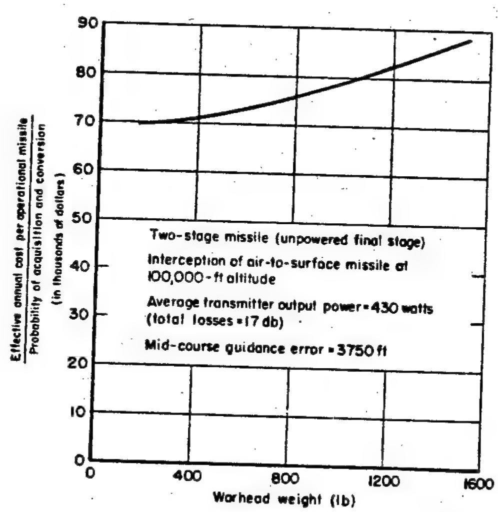

Fig. 58—Cost quotient vs warhead weight

and missile range, was accomplished in a similar manner. Warhead-weight choice is discussed below. Figure 58 shows

$$\frac{\text{effective annual cost per operational missile}}{\text{probability of acquisition and conversion}}$$

versus warhead weight for a typical missile range of 450 miles. The choice of missile range is influenced by considerations beyond the scope of this chapter—e.g., the target system to be defended and the planned radar network. These questions are treated in Part II of this report.

KILL PROBABILITY

The proper warhead design is as important as proper missile design. The single-shot kill probability depends on the missile miss-distance, warhead size, target vulnerability, and warhead design,[17] the latter depending on all of the preceding. Enough possible warhead types are presently conceivable that it is reasonable to impose the requirement that the missile warhead be substantially a *K*-kill (instantaneous kill) warhead. This is desirable to shorten the required missile range for a given defended radius. It also is desirable that the missile kill in the 1959 period be required to be the same against both manned aircraft and air-to-surface missiles.

Where miss-distances are as small as 20 ft, the following types of warheads are conceivable: (1) small high-velocity fragments—more is known about this type than about any other, but the airplane targets usually die slowly from a hit on a vulnerable part; (2) blast—this type of warhead has high *K*-kill effectiveness against aircraft and bombs for small miss-distances; (3) a collection of contact-fuzed blast pellets, with or without delay in the fuzes; (4) rods—this type appears to be effective against aircraft in that its *K*-kill ability is probably nearly equal to the slow kill ability of the small-fragment warhead; and (5) a collection of shaped-charge cubes.

None of these (except perhaps the latter, about which the least is known) seems to be equally good against both aircraft and missiles. Blast pellets, contact-fuzed blast pellets, and rods each have the property of killing an airplane quickly by destroying structures as well as vital parts (pilot, engine, etc.). For contact-fuzed blast pellets an undelayed burst is probably desirable. At present it seems that the blast warhead or the collection of blast-pellet warheads would be best for destroying airplanes but not for destroying missiles. This is because

the high speed of the missile might still carry the armed A-bomb warhead relatively close to the ground target even if the missile's controls were blown away. It becomes desirable therefore to design a warhead that will kill a missile and at the same time kill the bomb (prematurely explode it, or make it a dud). This can probably be done by high-energy (large-mass, large-velocity) fragments. A compromise warhead, which might be equally effective against aircraft and missiles, might then be one comprised of half contact blast pellets and half high-energy fragments. Against a Stalin aircraft and an air-to-surface missile, the kill probability of such warheads (using a VT fuze and the associated optimum burst pattern) would vary with warhead weight for a miss-distance of 20 ft, as indicated in Fig. 59 (page 190).

Combining the results of Figs. 58 and 59, the

$$\frac{\text{effective annual cost per operational missile}}{\text{(probability of acquisition and conversion) (probability of kill)}}$$

versus warhead weight was plotted (Fig. 60, page 190). The choice of a warhead weight of 750 lb appears reasonable. It should be noted that this corresponds to a desired kill probability of 0.9, a value which is considerably higher than current specification practice. The desirability of the 0.9 value is one of the strongest conclusions of this study.

After considering Fig. 60, and the preceding relations of design parameters, it was possible to specify the main design features of the generalized area-defense missile. (These are given in Table 13, page 186.) The resulting value of probability of acquisition and conversion was 0.85 against the Mach 3 enemy missile. Against manned bombers of higher echoing area, slower speed, and lower operating altitude, it would be approximately 1.0.

OPERATIONAL DEGRADATIONS

The missile itself was assumed to have a reliability factor of 0.85, based on an examination of the trends of the development of reliability in present-day missiles. Based on an extrapolation of World War II experience with ground radar, a ground-control-equipment degradation factor of 0.6 was used; this included both the effects of equipment failure and confusion. These factors are the greatest source of uncertainty in the final comparisons of weapons systems and influence the final results in a direct fashion. The succeeding calculations (in Part II) were arranged, when possible, so as to facilitate changes in degradation factors if better data became available.

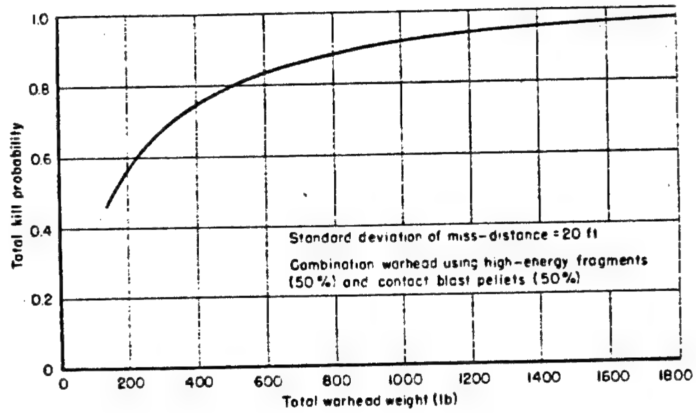

Fig. 59—K-kill probability on aircraft and missiles for dual-purpose warhead

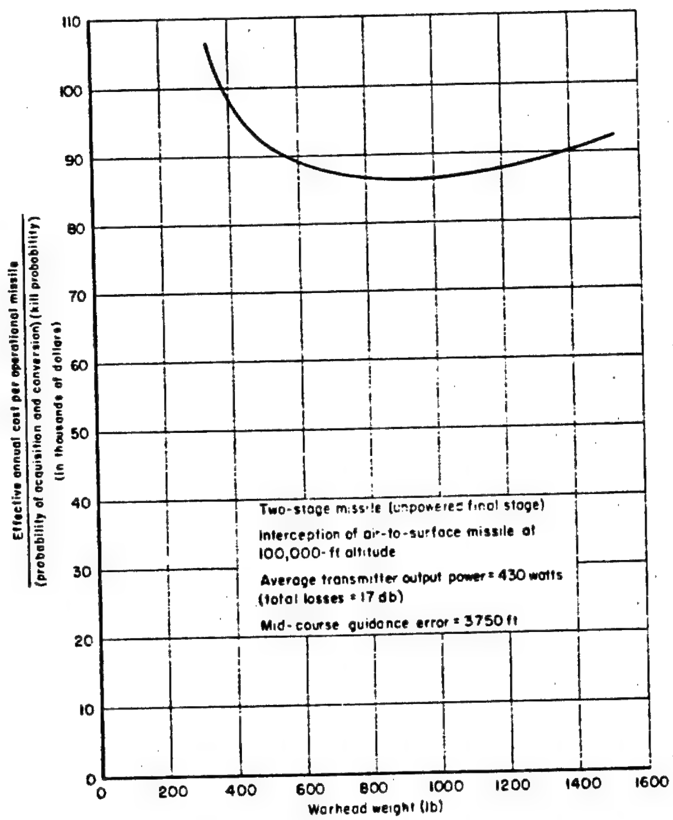

Fig. 60—Cost and effectiveness quotient vs warhead weight

There are other effects, such as electronic countermeasures, multiple-target separation, etc., which might seriously impair missile performance. No operational experience exists from which direct estimates of these factors can be made. However, in this study the missile was required to be so designed as to be unaffected by target-maneuver and multiple-target-resolution difficulties (the major degradations in the case of heavy AA guns in World War II). These problems, as well as the vulnerabiilty of the weapon to electronic countermeasures, were studied as separate questions. An attempt was made to design around some of the most serious electronic countermeasures. (See Chap. 16, Part II.)

IV. Area-Defense Missile Kill Potential

By using the numerical data given in the preceding discussion, it is possible to find the kill potential for combinations of offense and defense weapons. (See Chap. 7, page 126, for a discussion of kill potential, which was the basic measure of effectiveness into which the results of each component study were translated.) A commitment factor of two-thirds was used as a conservatism to allow the local commander a reserve in case of a raid subsequent to the one fired upon. Kill potential for a $1 billion annual defense budget was calculated by dividing $1 billion by the effective annual cost per missile (from Fig. 55, page 185). The quotient was multiplied by the following factors:

1. The two-thirds commitment factor.
2. The ground-system degradation factor of 0.6.
3. The missile reliability factor of 0.85.
4. The kill probability, which is 0.75 for the Bomarc I warhead and 0.9 for the 750-lb warhead.
5. The probability of acquisition and conversion, which is 0.85 against the Mach 3 missile for the seekers used here in the generalized missile. It is nearly 1.0 against manned bombers.

Ground-radar costs were not included in the calculations at this stage.

Figure 61 shows the kill potentials of Bomarc I and generalized area-defense missiles of 100-mile and 450-mile design radii. From this graph it can be seen that the generalized missile of 100-mile radius has only 25 per cent more kill potential than Bomarc I, which also has a 100-mile radius. The real advantage

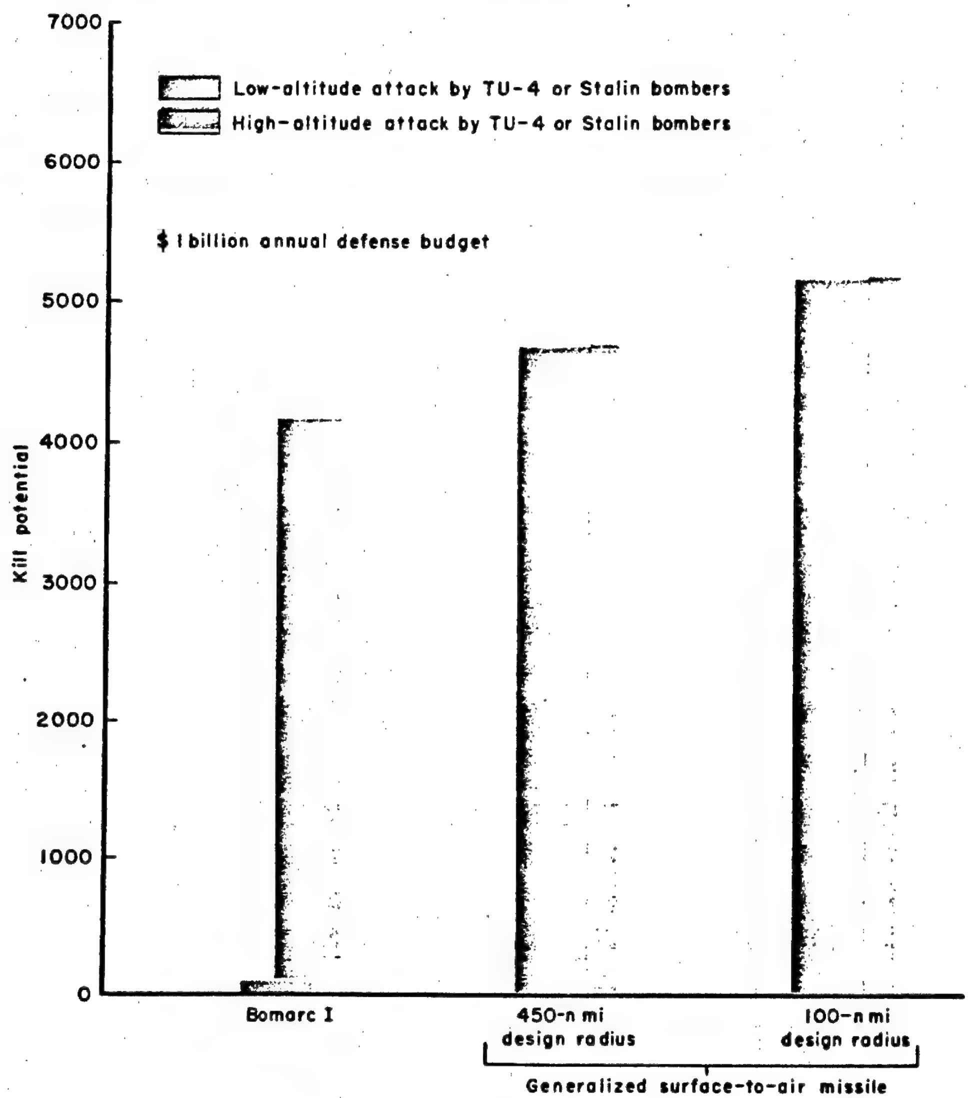

Fig. 61—Area-defense missile effectiveness

of the generalized missile is its ability to combat advanced threats, including enemy missiles at speeds of Mach 3 and altitudes up to 120,000 ft. From Fig. 55 it can also be seen that increasing the range from 100 miles to 450 miles does not entail enough added cost to lessen the kill potential very much, which means that ground-radar costs and relative technical feasibilities will dominantly affect the selection of a radius. This problem is treated in Part II of this report.

Actually, the commitment factor (given here as two-thirds) is properly a topic for Part II also, since its value logically depends on the amount of information available to the local commander, and therefore on the extent of radar coverage. In addition, it also depends on the forces of other weapons which could be brought to bear on later enemy attacks if the area-defense missiles were largely expended on the first attack.

Another factor (treated at length in Part II) reduces the number of missiles which actually engage the enemy. Depending on the "protected radius" and deployment of the defense missile, the geography of the target system, and the enemy's strategy and routes, some of the defense missiles will not have enemy bombers within their radii. Others will have only bombers which already have a high probability of being killed. This type of effect is *not* included in kill potential. As pointed out in Chap. 7, kill potential can be used *directly* only to compare similar weapons of about the same combat radius.

CHAPTER 9
LOCAL-DEFENSE MISSILES

I. Introduction

Local-defense surface-to-air missiles[1] will probably become operationally available several years before area-defense missiles reach field use. This is largely because straightforward guidance and control techniques may be used, the ground components being located in one place and built as one system. Some of these first missiles are being built without airborne seekers, thus avoiding another source of complication. The U.S. Army is organizing battalions to handle local-defense missiles; they have a nucleus of men who are now obtaining experience by working in the field alongside the technicians of the missile contractors. As will be noted below, some of these simple forms of guidance are costly. A completely different guidance technique is suggested and discussed in this chapter and in Chap. 12.

The fact that local defenses can protect only one target, or a few targets at best, whereas area defenses can protect many targets, makes it necessary to consider the target system and the detailed deployment of launching sites in order to compare the effectiveness of area-defense and local-defense missiles. An attempt was made to do this in RAND's Defense Systems Analysis, but it should be pointed out that the two types of weapons have differences which cannot be sharply reflected in numerical answers. In general, it can be said that most of the critical questions of feasibility are nearer to solution in the case of the local-defense missile, and this must be taken into account in arriving at over-all conclusions.

SCOPE

In the present study it was assumed that by 1955 both the Terrier I and Nike missiles could be operational in large quantities. By 1957 an improved or advanced version of the Terrier missile could be operational. This advanced Terrier-type missile would have a somewhat greater range, larger warhead,

[1] In RAND's study, local-defense missiles are considered to be those having ranges of less than 75 miles. Longer-range missiles are treated in Chap. 8.

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and more accurate tracking radar[2] than is visualized for the Terrier I. Instead of the advanced Terrier-type missile, the Talos missile might be operational in 1957. In addition, it was felt that another possibility might be to modify some existing missile and seeker programs to get into operational use by 1957 a missile having semi-active homing-all-the-way guidance and low-altitude capability. This missile would be analogous to the Bomarc I area-defense missile (although it is hoped that its versatility would be greater) in that it would make use of existing programs wherever possible. It would be an interim weapon because it would be an earlier, lower-capability version of a 1959 operational system. In the RAND study, this missile is called the *interim semi-active local-defense missile.*

Finally, it was estimated that in 1959 a completely new local-defense missile could become operational. This missile, designated as the *advanced generalized local-defense missile,* was the principal local-defense missile studied. It was selected, as will be described below, from a family of hypothetical missiles on the basis of lowest system cost for a given defense level against all the conceivable enemy threats for the time period studied.

The enemy threats assumed for the various periods considered have been described in Chap. 5 and range from the TU-4 and subsonic air-to-surface missiles, assumed to be operational in 1955, to the Stalin and Lenin aircraft and supersonic (Mach 3) missiles, assumed to be operational in 1959. The later carriers are assumed to be able to attack from any altitude between 200 ft and 100,000 ft and to use the unconventional tactics (such as feinting and the release of air-to-surface missiles after attracting defense-missile fire) discussed in Chap. 8.

II. The Nike, Terrier, and Talos Systems

This section presents numerical data on the ability of the planned missiles to cope with the conventional high-altitude attack. Their effectiveness against other attacks will be discussed qualitatively.[3]

Descriptions of the design and performance characteristics of the Nike, Terrier I, and Talos missiles were obtained from the missile contractors. The advanced Terrier-type missile was assumed to have a larger warhead, better

[2] This might be the Mk-49 radar or the Nike tracking radar.

accuracy, and higher performance than the Terrier I. Table 14 gives the characteristics of these four missiles.

Table 14

COMPARISON OF MISSILE CHARACTERISTICS

Missile	Range (mi)	Maximum Altitude (ft)	Average Velocity (Mach No.)	Warhead Weight (lb)	Warhead Type	Guidance Type
Nike	30	40,000	2.5	300	Fragmenting	Command
Terrier I	10	40,000	1.7	220	Fragmenting	Beam rider
Advanced Terrier-type	15	40,000	2.0	275	Fragmenting	Beam rider
Talos	50	40,000	2.0	310	Fragmenting or rods	Beam rider and semi-active homing

The Terrier I and advanced Terrier-type missiles have a beam-rider type of guidance system using a target-tracking radar. With this system, several missiles can be fired per salvo, but this salvo must be directed at one bomber. The miss-distance of the missile is determined by the radar tracking accuracy and the ability of the missile to ride the beam. Miss-distance increases with the distance that the missile flies and is assumed to be 1 mil for the Terrier I and ½ mil for the advanced Terrier-type, before operational degradations are applied. The time between salvos equals the missile flight time from launcher to target, plus 10 sec for radar assignment, slewing, and acquisition.

Multiple targets are assumed to be resolved by range and angular discrimination. They must be separated in range by about 200 to 300 ft and in angle by more than 1° (about 1000 ft at 10 miles). Over water, low-altitude limitations might be imposed on the Terrier guidance system because of reflections of the radar beam from the water; these reflections cause large elevation errors when the main tracking beam hits the surface of the water. Over land, such large specular reflections are less likely. However, ground-clutter signals might be larger than the target signal, which would cause the range gate to unlock.

DEPLOYMENT

An estimate was made of the best deployment of these weapons about three types of defense target systems: (1) a given number of isolated point targets, (2) a cluster of an equal number of targets, and (3) a target area assumed to have a value equal to the number of point targets considered. It was found that the attrition on the enemy air forces for a given defense expenditure was sufficiently alike for all of these so that in considering the defense of the actual United States target system, the attrition of enemy carriers could be calculated as if all the defended targets were isolated.

It was felt reasonable to deploy the missiles about the isolated targets to provide a defended radius of 10 miles, making a suitable allowance for target size, bomb error, bomb-release distance, and time for the bomber to die. With these requirements, it still turned out that all systems except Terrier I should have launchers centrally located.

NUMBER OF SALVOS

Assuming the launcher deployment and rate-of-fire limitations described above, and making a further assumption that missiles would be used only to prevent delivery of bombs,[4] the number of salvos each guidance station could handle against a high-altitude attack was calculated. The results are shown in Table 15.

[4] There is a small gain to be made at low defense levels if fire continues beyond the bomb release line, but this was neglected here.

Table 15

NUMBER OF SALVOS EACH GUIDANCE STATION COULD HANDLE AGAINST A HIGH-ALTITUDE ATTACK

Missile	Attacking Aircraft			
	TU-4, Nonfeinting	TU-4, Feinting	Stalin, Nonfeinting	Stalin, Feinting
Nike	3	1	2*	0*
Terrier I	1	0	1	0
Advanced Terrier-type	3	1	2	0*
Talos	11	6	7	2

*The number of salvos shown here was calculated by the exact rules set forth in RM-626 (see footnote 3, page 196). A looser construction of these rules, together with consideration of some of the practical possibilities of forward deployment at many United States targets, was used in computing the kill potentials given at the end of this chapter. The Nike missile was allowed 3 salvos against a nonfeinting Stalin; against a feinting Stalin, it was estimated to have half as much kill potential. The advanced Terrier-type missile was allowed one salvo against the feinting Stalin.

It was assumed that the defense would know when the enemy aircraft was not feinting and that it would fire as many salvos as it could, commensurate with the range limitation of its missiles. When the enemy bombers were feinting, it was assumed that the defense would hold its fire until it was sure that any released missile could catch the feinting bomber. Although not indicated in Table 15, the number of salvos against a subsonic air-to-surface missile released beyond the range of the defense missile is about the same as for the case of the nonfeinting Stalin bomber.

KILLS AND SALVO STRENGTH

In addition to the tactical and deployment studies mentioned, RAND made independent evaluations of missile kill probability,[5] ground organization, and associated systems costs.[6] Fragmenting warheads, capable of *C* kills against the various bombers attacking at high altitude, were assumed.[7] These assumptions permitted the calculation of mean kill probabilities over all the missile salvos. The mean kill probability per salvo includes the missile reliability assumption

[7] For a definition of kills, see Chap. 7.

and is calculated as $1 - (1 - P_K F_R)^{N_s}$, where P_K is the single-shot kill probability, F_R is the missile reliability factor, assumed here to be 0.85, and N_s is the number of missiles per salvo, as given in Table 16.

All of these missile systems have one feature in common: ground personnel and equipment costs, particularly those associated with guidance, are very large compared with the missile cost itself. In all four systems, a limitation is imposed on the system by the fact that one guidance section can direct missiles against only a small number of a closely packed group of enemy targets during brief engagements. In the Nike system, there is also a limitation on the number of missiles that can be directed by one guidance unit against a particular target. Since the single-shot kill probability of the Nike missile is small, it is always best to fire as many missiles at the target as the guidance system will allow, in order to increase cumulatively the kill probability of the system as a whole. (More missiles than the number handled by a single guidance unit may be required against a particular target; these would have to be handled by another guidance unit to achieve high attrition levels.) In the cases of the Terrier and Talos missiles, with their beam-rider guidance, a large number of missiles can be simultaneously directed against one target. Because of the diminishing return of cumulative kill, the effect of the cost of missiles used finally shows up, relative to the cumulative kill they produce, so that there is an optimum number of missiles to be handled by one unit in one salvo. Table 16 shows the optimum number of missiles per salvo and their mean kill probability against various enemy threats. The calculation of the results shown in this table depended on information given in Table 17.

COSTS

It is evident from the preceding discussion that a unit of ground-guidance equipment is used with a definite number of associated missiles. Table 17 shows the cost of a guidance unit* and of the associated missiles, men, and equipment for the various systems. Note that the total missile costs per guidance unit (obtained by multiplying the missiles per salvo, the number of salvos, and the cost per missile) are relatively small compared with the guidance costs.

The ground organization assumed in this study departs from that presently conceived by the Army in that some operational personnel were eliminated in favor of maintenance personnel so that the missiles could be maintained in a

* The costing procedure used here is similar to that described in the later discussion of the generalized local-defense missile

Table 16

OPTIMUM NUMBER OF MISSILES PER SALVO AND THEIR MEAN KILL PROBABILITY

Missile	Attacking Aircraft: TU-4, Nonfeinting	TU-4, Feinting	Stalin, Nonfeinting	Stalin, Feinting
	Optimum Number of Missiles per Salvo (N_K)			
Nike	(1)	...	(1)	...
Terrier I	5	...	5	...
Advanced Terrier-type	3	4	3	...
Talos	1	2	2	2
	Mean Kill Probability per Salvo			
Nike	.32	.42	.30	...
Terrier I	.83	...	.83	...
Advanced Terrier-type	.79	.90	.76	...
Talos	.64	.87	.87	.87

Table 17

EFFECTIVE ANNUAL COST PER GUIDANCE UNIT AND PER MISSILE

(Millions of dollars)

Missile System	Cost per Guidance Unit	Cost per Operational Missile
Nike	1.074	0.0745
Terrier I	0.797	0.0665
Advanced Terrier-type	0.743	0.0612
Talos	1.038	0.0631

ready-to-be-launched manner for a 4-year-preparedness period. This type of organization is ideally arranged for a threat in which it is assumed that the enemy would throw its entire forces against us in the first strike. (See the discussion in Chap. 8, and later discussions of the 1959 generalized local-defense missile for elucidation of the costing procedure.)

DEGRADATION FACTORS

In addition to the missile reliability factor of 0.85, included for the missile itself and accounted for in Table 16, the system operation should be further

degraded for confusion and unreliability of ground equipment. A factor of 0.4, applied directly to the kill potential (discussed below), is taken for the missile systems under discussion, except for the more advanced missile (the Talos), for which the factor used is 0.5.

SYSTEM EFFECTIVENESS

The above tables and numerical factors furnish the information needed for the computation of the kill potentials of Nike, Terrier I, advanced Terrier-type, and Talos missiles. The method of computation, together with a brief discussion of the effectiveness of these missiles, is given in the concluding part of this chapter. Two problems which were not taken into account in the numerical calculations will be discussed next.

Multiple Targets[9]

As in the study of area-defense-missile performance, it was assumed that the attacking bombers might attack under conditions of good or bad visibility, using various formation designs, etc. This raises the familiar problem of multiple-target resolution, previously discussed for area-defense missiles. The Terrier and Nike missiles have no seeker, so they must rely on the resolution of the target-tracking radar. As presently visualized, this radar would make use of range and angle resolution and would experience difficulty separating targets flying abreast spaced by distances of the order of hundreds of feet up to several thousands of feet. Although the range-tracking gates are made narrow to minimize this difficulty, it would seem that, at least under daylight conditions, bombers could fly in tight formation, perhaps jockeying back and forth slightly, and cause considerable trouble for the target-tracking radar. No quantitative estimate has been made of the reduction in missile effectiveness which this might cause, so no account has been taken of this effect in determining the kill effectiveness of these missiles. The Talos missile, as presently planned, would use an interferometer-type seeker and would depend on separating multiple targets by range resolution and angular-rate solution. It is felt that this type of seeker could satisfactorily resolve multiple targets.

Low Altitude Attack[16]

Local-defense missiles were assumed to be meeting bomber attacks at the same altitudes as those studied for the interceptor and area-defense missile, i.e., from bomber maximum combat altitudes (35,000 to 50,000 ft) to low altitudes. Missiles such as the Nike, Terrier I, and the advanced Terrier-type have a low-altitude performance limited by the capability of tracking radars at extremely low elevation angles. In addition, the Terrier missiles may be further limited by the angular dispersion in launching and the minimum elevation angle of the launching beam. There are possible modifications of these guidance systems which might improve the low-altitude performance. The low-altitude capability of the Talos missile is essentially dependent on the solution of seeker-design problems. It is doubtful whether the presently proposed seeker can achieve this capability.

III. Requirements for a New Local-Defense-Missile System—Selection of Semi-Active Homing-All-the-Way Guidance

ATTRITION LEVEL

When the information given above was used to obtain the final results of the Defense Systems Analysis (the numerical part of RAND's study), it turned out that all the missiles discussed so far would provide inadequate defense of the United States for reasonable budgets even against a high-altitude attack by subsonic bombers. (The Talos missile might be better than the others, but it would not give a high level of defense.) This shortcoming was discussed in Chap. 2, where it was also shown graphically in Figs. 10 and 11.

A new missile system must be sought to overcome this deficiency. Examination of the presently planned systems revealed that the ground equipment and associated personnel cost too much compared with the missiles used, since the missiles can only be used during the short time allowed by a concentrated raid. This characterizes rate-of-fire-limited systems. RAND's examination of the alternatives showed that the greatest reduction in this cost could be achieved by using a homing-all-the-way guidance system. Since the tactical conditions required missile ranges of 20 to 30 miles (as explained below), an active homing-all-the-way system was ruled out as too costly. Semi-active homing-all-the-way was thus chosen as the preferred guidance type. A cost analysis further

revealed that for the large raid sizes anticipated and the high defense level desired, ground illumination in a semi-active homing-all-the-way system could best be achieved by hemispherical fixed illuminators or by slowly moving wide-angle illuminators at the target, rather than by individual tracking illuminators. The latter would produce a system effectiveness not much better than the Terrier I, although it might be best for low (though uninteresting) defense levels. The fixed-illuminator system could obviously serve for any number of missiles against a concentrated raid, as the system is not rate-of-fire-limited. Further, cost reductions could be achieved through the use of vertical launching and continual maintenance[11] in a ready-to-go condition (eliminating expensive launchers and many operational personnel). Other system cost reductions may be achieved through efficient missile and warhead design (see below).

DIVERSE THREATS

In recapitulation, none of the presently planned missile systems—Nike, Terrier, or Talos—is expected to cope with the threat of a low-altitude attack. In addition, all of these systems may have severely reduced effectiveness against feinting and close-formation attacks. The ability of one of the systems to cope with subsonic missiles is essentially negligible, and the ability of all of them is negligible when the missiles employ tricky tactics. Yet it is anticipated that the enemy will fly at low altitude, use some tricky tactics, and have subsonic missiles during the expected operational period of these defense missiles.

The low-altitude threat was an additional and important reason for selecting homing-all-the-way guidance. Tracking radars, with or without MTI, have difficulty in pointing at low angles, particularly over water, because of reflections caused by the radar beam hitting the surface. In a homing system, these problems could be surmounted by programming the initial trajectory upward and approaching the target in a dive, thereby separating the target from its reflection by range discrimination. A further advantage exists over the mid-course–plus–homing system: The assignment of targets would be done on the ground, so that the distribution of missiles among enemy targets could be made uniform instead of random (or, perhaps, adversely biased), as might occur with seekers acquiring their targets only on the terminal phase of flight. Also, a longer time could be taken for range-angle or velocity searching, which would result in a simpler seeker design.

[11] This, incidentally, places an important development requirement on the missile powerplant, which was discussed in Chap. 8 for the area-defense missile.

The low-altitude problem would not be solved just by the choice of homing-all-the-way guidance. Specific seeker capabilities are desired and will be described. It was assumed that the ability to cope successfully with low-altitude aircraft and missile targets, tricky tactics, etc., would be "built in" the semi-active homing-all-the-way system, principally through requirements on seeker capabilities and secondarily through requirements on missile and warhead design.

Since a completely new system is sought, the principal attention in the remainder of this chapter will be given to what we call an advanced generalized local-defense missile to be operational perhaps by 1959. The characteristics of this missile were chosen by examining a family of possible missile designs and selecting a preferred one on the basis of least system cost to maintain a given defense level against the diverse threats of the time period concerned. The offense threats assumed for the 1959 period were TU-4, Stalin, or Lenin aircraft or enemy missiles attacking at any altitude up to 100,000 ft. The ability of the offense to use tricky feinting tactics and air-to-surface-missile release was also assumed.

IV. Advanced Generalized Local-Defense Missile—Semi-Active Homing-All-the-Way

TACTICAL REQUIREMENTS

Since the system will not be rate-of-fire-limited and the missile accuracy (discussed later) will be independent of range, launchers and fixed illuminators should be deployed as close as possible to the ground target they are defending. To cope with the low-altitude threat, the illuminators should be placed high enough to illuminate air-to-surface missiles at low altitude at about 20 miles (the reason for the choice of this range will be given below). Associated with this low-altitude illumination requirement is a corresponding requirement on the missile seeker that it be capable of turning more than 90° from the straight-ahead position in any azimuth, because the missile is launched from a vertical position. (A short preset vertical flight of 100 to 200 ft may be required for the missile to see its target for some low-altitude attacks.) To cope with missile and aircraft attacks from any azimuth, the illumination coverage must be completely hemispherical.

It is reasonable to require that the last target interception occur not closer than 5 miles (measured horizontally) from the defended point. The target

which would approach most closely before being intercepted would, of course, be the high-speed air-to-surface missile. (Likely relative average speeds of the defensive surface-to-air missile and the enemy air-to-surface missile will be used in the following discussion.) Consider an enemy missile that was intercepted at 5 miles; to accomplish this, a surface-to-air missile would have had to be released against it when it was about 14 miles distant. (The choice of this number, which depends on defensive-missile speed, will be justified below.) Then, if about 10 sec are required for assignment of defensive missiles against a closely packed group of air-to-surface missiles, the first in the group would have had a defensive missile sent against it when it was 19 miles from the target. An airplane pilot who was quite clever could have released his air-to-surface missile at 19 miles, just before an earlier defensive missile hit him; this earlier missile, to destroy the airplane at 19 miles, would have had to leave the ground when the airplane was 24 miles from the target. (The airplane would have traveled 5 miles while the defensive missile accelerated and went 19 miles.) A 10-sec assignment time for a salvo of missiles against the airplanes would correspond to about 1 mile of airplane travel. Therefore, this first airplane in the group would have had missiles assigned to it when it was 25 miles away. The foregoing conditions require that the defense, using a radar tracking the enemy carriers with range information, instruct a salvo of missiles to be fired at a close group of airplanes during a 10-sec interval when the first of the group reaches a distance of 25 miles from the target.[12] A second salvo of missiles would then be released when any of the enemy carriers (which would be indicated by remaining radar signals) crossed a line 19 miles from the target. This two-salvo technique is necessary to ensure that all the aircraft and missiles are killed separately if the enemy is tricky enough to make the defense fire at both. With this doctrine, the enemy planes which reach the first assignment range may turn in a feint, so that the missiles assigned against them must chase and catch them. These tail-chase interceptions would occur at about 28 miles. This condition, together with the requirement that the action described take place at low altitude, establishes a missile range requirement of 28 miles at sea level.[13] These conditions also set the radar power requirements.

[12] Prior to this assignment, the system operation would require gross information regarding raid strength, direction, and structure, so that the proper number of missiles could be alerted. This could be accomplished by an acquisition radar

For a given missile-dish size, the radar should be sufficiently powerful to illuminate air-to-surface missiles at 19 miles. Because of the difference in the size of air-to-surface missiles and aircraft, this same radar could illuminate aircraft considerably beyond the required 28-mile distance. However, the extra power could be considered partially to offset jamming by manned aircraft.

The required missile and radar range is mainly influenced by the nature of the enemy threat. However, it is also influenced by another *missile* design feature: the average velocity during flight, particularly during the first 5 miles. An increase in this speed would allow a decrease in the missile range and in the radar range. A rough optimization of the radar-dish size and the missile average velocity was made in the context of the combined cost of the missiles, the ground equipment, and personnel. For instance, as the radar-dish size increases, the missile cost increases, whereas the ground-radar cost decreases; and as the missile average speed increases, the missile cost increases and the radar cost decreases. The optimum values of the variables depend also on the defense level. For a high defense level (about 10,000-ready missiles in the United States), the optimum dish size is about 2 ft in diameter and the average missile speed is that obtained by a missile initial acceleration of $6g$ followed by a thrust which sustains the velocity at about 3000 ft/sec. This design corresponds to the missile range requirement of 28 miles and to the previously discussed associated target ranges at the time of missile release.

There are certain assumptions to be made about the proper assignment of defensive missiles to enemy carriers, the recognition or nonrecognition of dead bombers during the engagement, and the number of separate missile salvos fired in the engagement.

There is some indication that a better than random distribution of missiles over targets can be achieved for semi-active homing-all-the-way missiles. Furthermore, at least a partial recognition of dead bombers should be possible, thereby permitting missiles to be fired in several salvos. To be conservative, however, it was assumed, for purposes of calculating system effectiveness, that only random assignment would be achieved and that there would be no recognition of dead bombers during the engagement.

GUIDANCE

Once semi-active homing-all-the-way guidance has been elected, it is necessary to discover the performance characteristics required.

The resolution of multiple targets can be achieved either by range and angular discrimination or by range and velocity discrimination. Both methods were

studied. (See Chap. 12.) Of the two, range and velocity discrimination, i.e., the use of pulse-doppler techniques, is believed to be the better method.

The elimination of ground-clutter signals was assumed to be an important element in the design of the seeker for the advanced generalized local-defense missile. This problem is also discussed in Chap. 12. Velocity tracking was proposed.

The miss-distance of the generalized missile was assumed to depend only on guidance and control during homing and was estimated to be 20 ft, as it was for the area-defense missile. The conditions, assumptions, and calculations of this study are given elsewhere.[14]

The range of the preferred pulse-doppler seeker was fixed by the requirement that there be a high probability of detecting an air-to-surface missile at a 20-mile range. This performance is adequate to permit detection of a manned bomber at greater ranges, another requirement of the study. For all-around illumination, about 500-kw average power is required if a 2-ft antenna is used in the missile.[15] In this study the criteria of a 50 per cent blip/scan ratio and a 1-m^2 (fluctuating) echoing area were used in the power determinations.

The proper missile-system operation would require a suitable acquisition system in addition to the illuminating radar. The acquisition phase (target assignment) could probably be accomplished by the use of a local-defense assignment-and-control center, which was assumed to be similar in size and cost to the present-day AN/CPS-5 radar and operations room. This center would receive information from the Air Force low-altitude radar network.

GROUND ORGANIZATION: MEN, EQUIPMENT, COSTS

As in the study of area-defense missiles, the principle behind the organization of launching personnel and equipment for the local-defense missile system was assumed to be the maintenance of missiles in a ready-to-launch condition at all times, thereby reducing the need for four shifts of operational personnel. The missile electronics system and powerplant would be checked daily and there would be a major overhaul every 6 months.

A guidance section is made up of one ground-guidance unit and all the associated personnel and equipment. A launching section comprises a reasonable

[15] If tracking illuminators are used, the power required of each one is considerably less, by a factor of about 1/500, but the complexity of the ground system increases. These counterarguments are also discussed in Chap. 12.

number of operational missiles (say, 40) and all of their associated personnel and equipment. In the case of rate-of-fire-limited systems, like the early missiles systems, the ratio of the number of their sections used depends essentially on the number of missiles that a guidance unit can handle in a concentrated raid.

On the other hand, in the case of the homing-all-the-way system, which is capable of an unlimited rate of fire, there is one guidance section per local-defense area. This includes the hemispherical illuminators, the acquisition radar, and their associated men and equipment. The number of launching sections (each having 40 operational missiles) used with the guidance section depends on and varies with the level of defense desired. The organization and cost breakdowns of the launching and guidance sections are given in Tables 18 and 19.

Table 18

GENERALIZED LOCAL-DEFENSE-GROUP MANNING

Manpower Requirements for Separate Generalized Local-Defense Launching and Guidance Sections

(All-around illuminators)

Function	Launching Section	Guidance Section
Operational functions:		
Officers	5	4
Missile testing	16	0
Assembly and repair	26	5
Operations	25	18
Radar		
Acquisition	0	24
Illuminating	0	14
Total	72	65
Support functions:		
Officers	9	8
Security	15	17
Fire protection	7	5
Transport	7	4
Food service	12	10
Supply	8	7
Maintenance	15	15
Medical	5	5
Headquarters and miscellaneous	16	15
Total	94	86
TOTAL MANPOWER REQUIRED	166	151

Table 19

GENERALIZED LOCAL-DEFENSE-MISSILE EQUIPMENT COSTS

Equipment	Number Required per Section	Unit Cost ($)
Launching section:		
Missiles	80	31,900
Launchers	40	600
Fire-control and testing panels	1	150,000
Missile-handling equipment	1	110,000
Organizational equipment	1	227,000
Guidance section:		
Illuminator transmitter	1	2,356,000
Acquisition radar	1	780,000
Communications and associated equipment	1	200,000
Organizational equipment	1	206,000

The organization of the launching section is similar to that described for the area-defense missiles in Chap. 8. It has an effective annual cost of $968,000 for personnel and $328,000 for equipment and facilities. Both of these sums include an amortization of initial costs over a 4-year period; allowances were made for the re-use of existing facilities wherever possible. The launching section cost may be prorated per operational missile; if so, the effective annual cost per operational missile may be approximated as 0.96 times the missile manufacturing cost, plus $32,400. The first term includes the purchase price of all defense missiles—those used as ready and reserve missiles, as spares, and for practice firings—and other charges, such as transportation, overhead, etc. This means that the cost per ready missile over its 4-year life is 3.8 times the manufacturing cost. The second term includes the costs of equipment, personnel, and facilities. As in the case of the area-defense missile, and for the same reasons, these costs embody the assumption that for every ready missile, 2.3 extra missiles are bought. Missile manufacturing costs were deduced from estimates of the number of manufacturing man-hours required to produce the various principal missile parts. (These will be given below, for the specific missile design chosen.) Guidance-section annual effective costs of $2,330,000 per section were always carried separately because, unlike the other costs, they depend on the geography of the defended targets. A detailed discussion of all of these matters will be found elsewhere.[16]

MISSILE DESIGN[17]

The missile design requirements specify that it have a short time of flight at low altitude (for tactical reasons), reasonable skin temperatures, a rather large body diameter to incorporate a large seeker dish, and that it be vertically launched (for operational reasons). The short-time-of-flight requirement determined the choice of a rocket powerplant. The low-altitude flight suggested a boost-cruise two-stage missile. However, it was found that because of the large missile diameter required, an integral one-stage boost-cruise missile is as efficient as a two-stage missile. Also, a one-stage missile is shorter in length and eliminates the booster disposal problem. Since the launching is to be vertical, the boost phase should not have too large an acceleration.

The compromise on the tactical, launching, and skin-temperature requirements, together with the interaction of the ground-radar power requirement, led, on the basis of least system cost, to the previously described design. This missile has a 28-mile sea-level range, a body diameter of 30 in., and a two-phase thrust program characterized by an initial acceleration of $6g$ followed by a Mach 3 cruise speed. The skin temperatures in flight were found to be still high enough (1160°R) to require that the radome nose be constructed of ceramic sandwich material. It is desirable that the missile be propelled by a liquid-fueled rocket motor using gasoline and nitric acid because of their availability and their high specific impulse, density, and convenient storage properties. Solid propellants would be equally satisfactory, and the actual choice would be dictated by the relative success, in the next few years, of development efforts devoted to two-phase-thrust solid- and liquid-fueled rocket motors.

Flight paths of the missile were calculated on the basis of vertical launching, a programmed turn, and a simple gravity turn into the enemy target; this was assumed to be a reasonable approximation of the proportional navigation homing course. The vertical launching, together with the turning requirements, dictated the use of a gimbaled liquid-fueled motor, or the use of jet blades for the solid-fueled rocket. The effect of missile dynamics on missile range, and specifically the effect of jitter caused by radar noise, were found to be unimportant for the sea-level design range. Also, the decreased range due to noise jitter at higher altitudes was more than compensated for by the increased range due to lower air density.

Because other design requirements resulted in a fat missile, the body lift is sufficient to satisfy the requirements of a $15g$ maneuver capability necessary to

minimize the effect of a 1g enemy maneuver capability. Thus, the configuration desired is that of a wingless missile with a movable cruciform tail. With a warhead weight of 750 lb (see below), the missile weight is about 5 tons for a 28-mile range at sea level. The manufacturing cost of the missile is estimated to be $31,900. This results in an effective annual cost per operational missile of $63,100. A sketch of the missile is shown in Fig. 62 (page 214). Its descriptions is given in Table 20, below.

Table 20

ADVANCED GENERALIZED LOCAL-DEFENSE MISSILE

Semi-Active Homing-All-the-Way

Enemy Threat: Mach 1.3 bombers and Mach 3 air-to-surface missiles

Warhead weight	750 lb
Range at sea level	28 nautical miles
Mach number during cruise at sea level	3
Useful ceiling altitude	About 60,000 ft
Normal load	15g
Body diameter	30 in.
Radar antenna diameter	23.5 in.
Over-all length	42 ft
Guidance	Seeker employs pulse-doppler techniques for multiple-target and ground-clutter discrimination
Propulsion	Dual-thrust liquid-rocket motor (boost thrust = 70,000 lb; cruise thrust = 15,000 lb)
Propellants	JP-3 and white fuming nitric acid; gimbaled motors at low speeds; movable fins at high speeds; no wings
Gross weight	11,700 lb
Manufacturing cost	$31,900

KILL PROBABILITY AND RELIABILITY

The considerations affecting the choice of an area-defense-missile warhead type apply equally well to the selection of a local-defense-missile warhead. However, the desirability of *K*-kill warheads is even greater, for obvious reasons. As in the study of the area-defense-missile system, consideration of missile launching cost and kill probability resulted in an optimum desired kill probability of 0.9. With a combination of large fragments (to kill the A-bomb) and blast (to kill the airplane) in the warhead, the desired size was found to be 750 lb.[18] The reasons for the choice of this warhead type were explained

in Chap. 8. As in the study of the area-defense missile, the missile reliability was assumed to be 0.85 and the ground-system degradation, 0.6. Potential degradations caused by certain electronic countermeasures have been accounted for by the design of counter-countermeasures. In one case, extra power for the illuminator radar has been provided to counteract enemy jamming. Other countermeasures are discussed in Chap. 16, Part II. The effectiveness of the advanced generalized local-defense missile, in terms of its kill potential, is discussed in the last section of this chapter.

V. Interim Local-Defense Missile—Semi-Active Homing-All-the-Way

To meet the lesser threat of subsonic aircraft and air-to-surface missiles, including the operational facets of the threat (high- and low-altitude attack, tricky tactics, etc.), it was found permissible to reduce the missile and radar design requirements and to design a system that could be operational in 1957. The missile range requirement was found to be about 20 miles and the radar range requirement, for detection of an air-to-surface missile, was found to be about 10 miles. (The range for release of defensive missiles against the attacking aircraft was found to be about 15 miles.) The 20-mile missile could be designed to have a cruise (and maximum) speed of Mach 2, together with a simple $3g$ initial-acceleration constant-thrust program to reach that speed. With a 19-in. dish diameter and 500-lb warhead, the missile was estimated to weigh 4190 lb and to cost $16,300. The effective annual cost per operational missile was estimated to be $51,700. The power required for the ground radar was estimated to be about 100 kw of average power, resulting in a total system cost of $1.56 million annually. A sketch of the missile is shown in Fig. 63 (page 214) and its description is given in Table 21 (page 215). The smaller warhead weight (500 lb) was again assumed to give a 0.9 kill probability, because of the greater vulnerability of the enemy aircraft in the 1957 period.

The remarks on the *general* nature of the *advanced* missile and its behavior (such as seeker requirements, etc.), presented in the sections on guidance, costs, reliability, and missile effectiveness, apply equally well to the *interim* local-defense-missile system. This, then, strongly suggests the need for one development program having two phases: the interim and the advanced missiles, together with their associated radar, as described in this chapter.

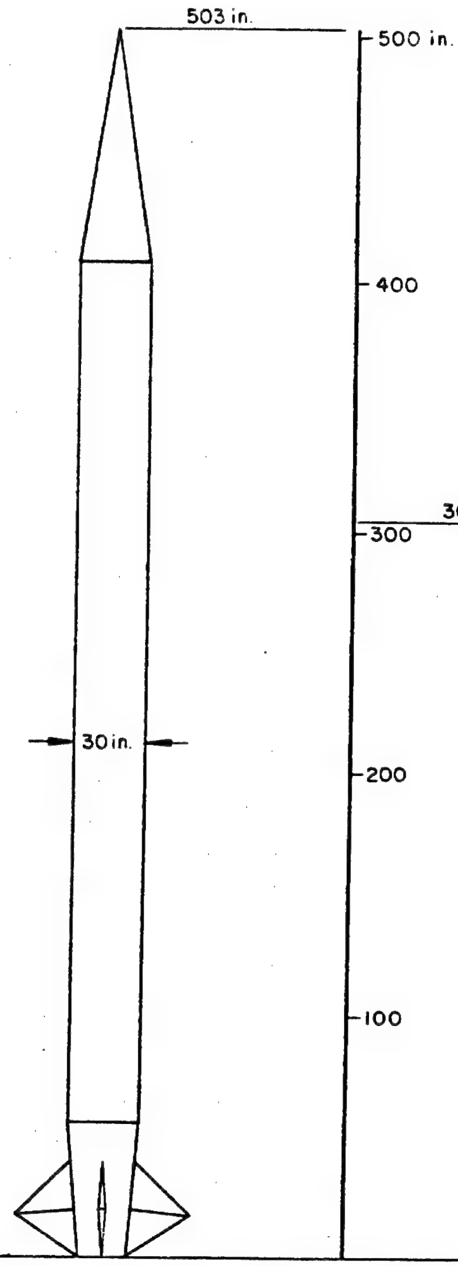


Fig. 62—Advanced generalized local-defense missile (semi-active homing-all-the-way)

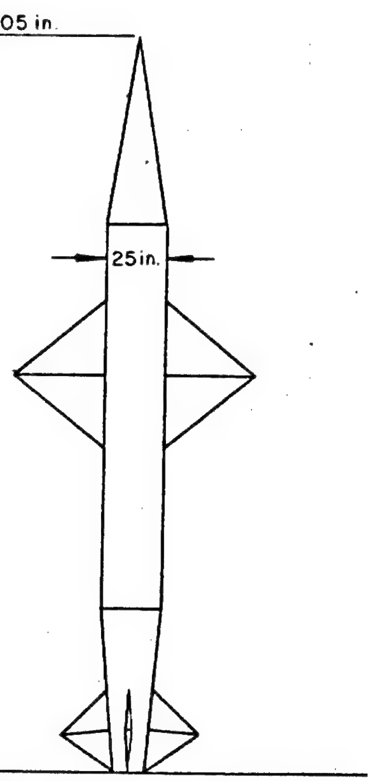


Fig. 63—Interim local-defense missile (semi-active homing-all-the-way)

Table 21

INTERIM LOCAL-DEFENSE MISSILE

Semi-Active Homing-All-the-Way

Enemy Threat: Subsonic bombers and missiles

Warhead weight	500 lb
Range at sea level	20 nautical miles
Mach number	2
Useful ceiling altitude	About 60,000 ft
Normal load factor	12g
Body diameter	25 in.
Radar antenna diameter	19 in.
Over-all length	25.4 ft
Guidance	Semi-active homing-all-the-way
Propulsion	Single-thrust liquid-rocket motor (cruise thrust = 6300 lb)
Control	Gimbaled motor all the way; fixed monowing; wing-to-frontal-area ratio (S/A) = 4.7
Gross weight	4190 lb
Manufacturing cost	$16,300

VI. Kill Potentials per Target—Local-Defense Missiles

Kill potentials[19] of the local-defense missiles are found in a similar way to those of the area-defense missiles. Two additional factors must be taken into account, however. First, for missiles that are fired in salvo, the mean kill probability of the salvo must be used, instead of the kill probability of a single missile. Secondly, the guidance costs must be taken into account. (This was not done in the case of the area-defense missiles, where the guidance comes from the main Air Force ground-radar network. These costs were included at a later point in the synthesis.) A commitment factor of two-thirds is again used as a safeguard against firing all the missiles against the first raid, and then having a later raid go unharmed.

For local-defense weapons, the RAND Air Defense Study found kill potential *per target* for a given annual defense budget per target. Because the number of guidance units in the non-rate-of-fire-limited systems depends on United States target geography, and not on defense strength, two slightly different ways of computing kill potential were used.

[19] For a definition and discussion of kill potential, see Chap. 7, page 126.

For rate-of-fire-limited systems (Terrier I, Nike, advanced Terrier-type, or Talos missiles), the kill potential per target for a \$5 million annual defense budget per target is:

$$\frac{(\text{ground-system degradation factor})(\text{number of salvos})(\text{mean } P_K \text{ per salvo})(5 \times 10^6)}{(\text{guidance cost}) + (3/2)(\text{number of salvos})(\text{missiles per salvo})(\text{missile cost})}.$$

The ground-system degradation factor, as previously stated, was assumed to be 0.4 for the Terrier I, Nike, and advanced Terrier-type missiles and to be 0.5 for the Talos missile.

The number of salvos is given in Table 15 (page 199), the mean kill probability (mean P_K) per salvo and number of missiles per salvo (N_S) are given in Table 16 (page 201), and the costs are given in Table 17 (page 201). The inverse of the two-thirds commitment factor appears as the coefficient of missile cost, and the 0.85 missile reliability was taken into account in deriving Table 16.

For non-rate-of-fire-limited systems (the advanced generalized and interim semi-active missiles), the kill potential per target for a \$5 million annual defense budget per target is:

$$\tfrac{2}{3}(\text{ground-system degradation factor})(\text{missile reliability})(P_K) \times \frac{5 \times 10^6 - \text{illuminator cost}}{\text{cost per missile}}.$$

As previously noted, a degradation factor of 0.6 and a missile reliability of 0.85 were estimated. The kill probability, P_K, is approximately 0.9 for both, although the warhead of the advanced missile is larger, to counter more advanced threats. The cost per missile (effective annual cost), as given above, is \$51,700 for the interim missile and \$63,100 for the advanced missile. The illuminator costs are the amounts cited above: \$1.56 million for the interim system and \$2.33 million for the advanced system.

By using the relations given above, kill potentials per target were calculated for local-defense missiles against the TU-4 and Stalin bombers. The results are shown graphically in Figs. 64 and 65. A wide range of values was found because of the wide variety of designs over the period of study. It can be seen that the advanced Terrier-type missile was much better than Terrier I. One reason for this is that the Terrier I was originally designed for Navy applications, whereas certain restrictions were removed in the hypothesized advanced Terrier-type and it was assumed to be intended primarily for land-based defense. Note that the semi-active homing-all-the-way missiles perform about the

same against both bombers, and without regard to whether or not they are feinting. (The differences in kill probability were small enough to be neglected.)

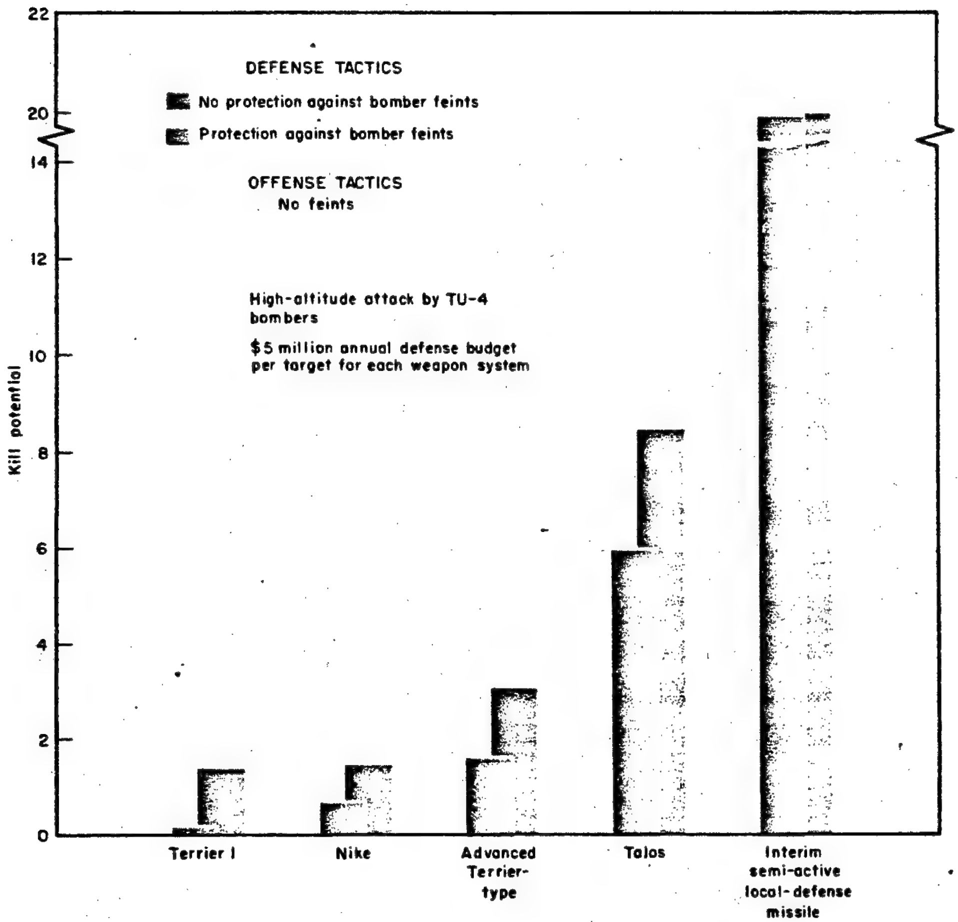


Fig. 64—Local-defense missile effectiveness against TU-4 bomber

The kill potentials against *subsonic air-to-surface* missiles are approximately the same as those against the nonfeinting Stalin bomber, except for the Talos, whose ability against missiles is doubtful because of its seeker properties. If air-to-surface missiles were released in the tricky manner described at the beginning of Chap. 8, the capabilities of Nike, Terrier I, and the advanced Terrier-type would also be doubtful. Against *supersonic air-to-surface missiles,* only

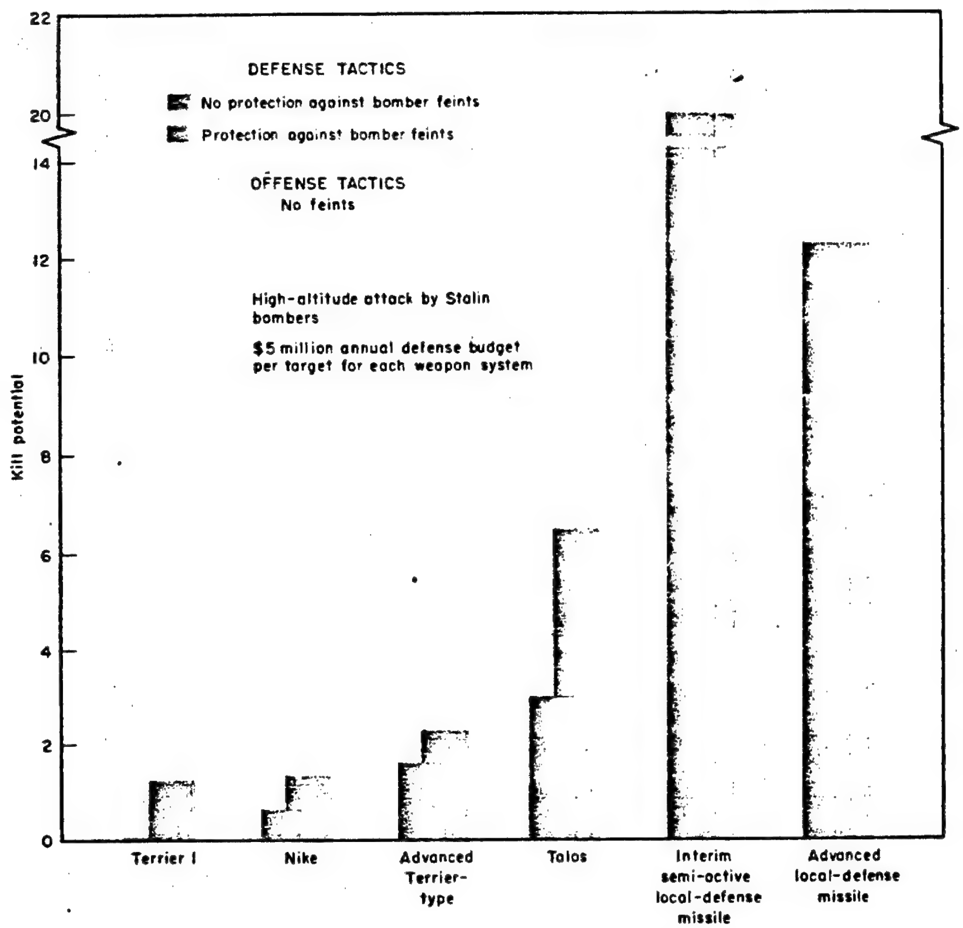


Fig. 65—Local-defense missile effectiveness against Stalin bomber

the advanced generalized local-defense missile has any effectiveness. It is because of added costs in designing against these supersonic enemy missiles that the kill potentials of the advanced missile are lower than those of the interim missile, as shown in Figs. 64 and 65, where the threats are bombers.

CHAPTER 10

UNGUIDED WEAPONS

I. Introduction

A considerable number of unguided antiaircraft weapons—guns and rocket launchers—were investigated during the preliminary phases of RAND's defense study. Since a great variety of such weapons might be available during the time period of the study, it was necessary to make a selection of the most interesting weapons to be investigated in detail. In some cases this was done by considering one weapon to be typical of similar weapons. It was also found, in preliminary studies of the effectiveness of unguided weapons for *high-altitude* defense, that

1. Barrage rockets and 90- and 120-mm guns are not so effective, by a considerable margin, as other weapon systems of the same cost when considered for the defense of the ZI. The attrition that they can achieve against missiles or maneuvering aircraft at high altitudes is practically negligible, and their value in spoiling bombing accuracy is uncertain.
2. The 90- and 120-mm guns are inferior to light antiaircraft guns for low-altitude use. This inferiority is primarily due to their greater cost and lower rate of fire.[1]

For these reasons the 90- and 120-mm guns were not carried into the later phases of the quantitative study, and barrage rockets were not considered further for high-altitude defense. There are two factors, external to the numerical study, that should be mentioned in this regard. First, the big antiaircraft guns are now in service use and are relatively mobile. It may be that they could be used to take advantage of a failure on the part of the enemy to use tactics as severe as those postulated for RAND's numerical analysis. The Soviet attacking force may not be able to maneuver effectively or it may not have an operational capability above medium altitudes. Secondly, it is particularly true that all the unguided weapons could play an important wartime role in addition to being

employed in the defense of the ZI, so that their uses, as considered in RAND's study, may be secondary uses.

Against a *low-altitude* attack, light guns and rockets proved to be the most effective. This, together with the probable inadequacy of interceptors and guided missiles in coping with a low-altitude attack in the earlier years of the study, made the role of low-altitude unguided weapons quite important.

The threats against which these weapons would be used were assumed to be the TU-4, the Stalin and Lenin bombers,[2] a subsonic air-to-surface missile, a supersonic air-to-surface missile, and V-1–type missiles launched at coastal cities from submarines.

It was assumed that the low-altitude attack might come under conditions of good or bad visibility and that this would have a marked effect on the altitude and formation-keeping ability of the enemy bombers.

The questions of minimum altitude and formation design are very important in the evaluation of the effectiveness of the low-altitude unguided weapons. Detailed consideration was given to the altitude profile of the attacking bombers. Two cases were chosen as typical:

1. In a daylight attack, the bombers might fly as low as possible through the radar early-warning belt and interceptor combat zone. This altitude was assumed to be 200 ft. They could then continue to fly at minimum altitude into the local-defense zone and rise only at the end of their flight to deliver the bomb at optimum height. If this were done by having the bomb explode in the aircraft, it would require a climb to approximately 500 ft to allow the crew to bail out (provided this was part of the plan), followed by a programmed zoom at the last minute to an altitude of 1500 to 2000 ft. The characteristics of the TU-4 bomber are such that this zoom would require a horizontal travel of only 1 mile.[3] The bomber would be above its minimum altitude for such a short time that interceptor defenses could not be brought to bear. In fact, local-defense guns could not take much advantage of the increase in altitude. In calculating attrition for this case, it was assumed that altitude would be held at 200 ft throughout the flight profile.
2. In a night attack at low altitude, the bombers might try to penetrate the radar network and interceptor defenses at as low an altitude as pos-

[2] These two higher-performance bombers would have reduced effectiveness at low altitude because of their jet powerplants; therefore they seemed to be a less likely threat.

[3] Starting from sea level at maximum speed, the TU-4 bomber could reach various altitudes in

sible. This was assumed to be at about 1500 ft over land and 200 ft over water. Bombers could maintain an altitude of 1500 ft over local defenses and the bomb could be exploded in the aircraft.

The possibility of a low-altitude attack terminated by a zoom climb over the local defenses was also considered. The purpose of the climb would be to engage the low-altitude weapons at an altitude at which their efficiency had fallen off. However, an inspection of the weapon combinations appropriate to the several time periods considered by the study shows no seriously weak zone between the domains of action of the high-altitude and low-altitude defense weapons, with the following reservation. Among the local-defense weapons, one with medium-altitude all-weather capability must be used in significant numbers. This could be the Terrier, the Skysweeper, or the Loki (the last two are described below). The zoom-climb tactic would probably be effective against local defenses consisting of combinations of light guns or of the T-131 rocket gun used in conjunction with the Nike missile or automatic barrage rockets (these light guns and the T-131 rocket gun are described below). For this reason the Terrier and Skysweeper were favored in selecting weapon combinations in the present study.

II. Formation Patterns

The formation-keeping ability of the enemy force has great bearing on the effectiveness of the low-altitude local-defense weapons. In the case of the interceptor defenses, and of at least the longer-range local-defense missiles (Nike and Talos) discussed in Chap. 9, it was felt that bombers would fly

the times shown in the following table:

Altitude (ft)	Time (sec)	Speed (knots)	
0	0	285	
100	2.2	280	
200	3.1	276	
500	4.9	262	zoom climb
1000	7.4	242	
1500	10.0	220	
2000	13.0	197	
2500	18.0	178	
5000	90.0	165	
10000	243.0	177	steady rate of climb
20000	590.0	208	

close enough together to divide the fire of the defenses. Thus, for example, a bomb carrier escorted by three other aircraft could expect only about 25 per cent of the firepower to be directed against it. It was believed to be questionable whether bombers could fly close enough together to divide the fire of the 10-mile-range Terrier I, particularly in the night attack. The low-altitude guns and rockets considered in this chapter have a much shorter range (on the order of 1 to 2 miles) and bombers would have to fly a much tighter formation to divide the fire of these weapons.

The formation-keeping ability required is within the capability of our own USAF bombers in daylight for short missions. To meet the requirement at night would necessitate the development of station-keeping aids and techniques, even for fairly short missions. On maximum-range missions, such as would be required for TU-4 attacks on this country, it seems very questionable whether such tight formations could be achieved because of the rendezvous problem and because of the effect on airplane range of strict speed control. As a result of these difficulties, two quite different cases were assumed for this study:

- That only single bombers would fly over the low-altitude unguided weapons.
- That very tight formations would be possible and that bombers would succeed in dividing the defense fire completely.

III. Weapon Characteristics

The weapons studied and their estimated availability dates were as follows:

By 1953, 50-caliber guns, 20-mm guns, 40-mm guns, Loki barrage rockets, the Skysweeper 75-mm gun, and the Stinger 60-caliber gun were all considered to be available.

By 1955, three new low-altitude weapons could become operational: a "new" 30-mm gun, which has been called the "BRL gun"; the T-131 rocket gun;[4] and an unorthodox automatic-barrage-rocket system.[5]

The 50-caliber guns and the 20-mm guns compete directly with the 40-mm gun as daylight defense weapons and were found to be less effective for the

[4] The T-131 is a more or less conventional, low-muzzle-velocity, high-rate-of-fire gun which fires a shell-rocket. After leaving the barrel, the shell uses rocket thrust to develop high velocity.

[5] This weapon system consists of an emplacement of rockets in a ring around the defended point. The rockets would fire vertically and automatically by means of a "VT-fuze barrier" through which the target aircraft must pass.

uses considered in this study and are not discussed further. The "new" 30-mm gun is based on a Ballistic Research Laboratories study and represents an advancement in gun design for the special purpose of defense against daylight low-altitude bombers. However, it was seen to be inferior to the T-131, which is already under development, and was therefore dropped from the study. The Loki, Skysweeper, and automatic-barrage-rocket defenses represent somewhat different approaches to the problem of bad-visibility low-altitude defense. (The Stinger was found to be inferior to the Skysweeper in obtaining the fast type of kill desirable in this application and was dropped from the numerical analysis.)

The characteristics of the guns and rockets considered in this chapter are given in Tables 22 and 23, below.

Table 22

UNGUIDED WEAPON CHARACTERISTICS—GUNS

Weapon Characteristics	Skysweeper, 75 mm	BRL Gun, Twin 30 mm	Automatic Gun, Quad 40 mm	Rocket Gun, T-131
Muzzle velocity, ft/sec	2,825	2,000	2,800	2,800*
Rounds per minute per mount	45	1,600	480	550
Projectile type	HE	HE	HE	HE
Projectile weight, lb	12.2	0.56	2.0	4.1
HE weight, lb	1.64	0.20	0.15	1.0
Complete round weight, lb	21.5	0.95	4.6	11.0
Fuze	Contact	Contact	Contact	Contact
Guns per mount	1	2	4	1
Weight of mount, lb	19,000	1,600	5,850	4,000 to 5,000
Fire control	Radar	Visual	Visual	Visual
Maximum effective range, ft	18,000	7,500	7,500	7,500

* Maximum, after burn-out.

Table 23

UNGUIDED WEAPON CHARACTERISTICS—ROCKET WEAPONS

Weapon Characteristics	Loki	Automatic Barrage Rockets
Burn-out velocity, ft/sec	4,500	2,000
Launcher capacity	64*	....
Type of warhead	HE, Contact	HE, Contact
Missile weight, lb	5.5	16
HE filler weight, lb	2.0	2.2
Complete round weight, lb	24.0	23.0
Mount	90 mm (M2)	....
Weight of mount, lb	40,000	....
Maximum effective range, ft	20,000†	....

* Rate of fire per minute per battery = 256.
† For low-altitude targets.

The *visually fired* guns were assumed to be directed by something similar to the M5A2 director. The *Skysweeper* has on-carriage radar fire control, the characteristics of which are approximately the same as those of the Bell Laboratories T-33 system. The Loki has about the same fire-control performance characteristics as those of the Skysweeper. Because of line-of-sight limitations, a maximum detection range of 14,000 ft and an open-fire range of 7500 ft were assumed for 200-ft targets for all weapons. A detection range of more than 50,000 ft and an open-fire range equal to maximum effective weapon range were assumed for 1500-ft targets. The guns were assumed to fire until slewing-rate limitations caused them to lose track of the target as it flew overhead. Later, as the target receded, it was assumed that the gun could again track and fire. A conservative assumption was made that the visually controlled guns would have no nighttime capability. It is quite possible that development in the use of searchlights, flares, or some other visual aid may give these guns nearly equal effectiveness at night or in daytime. In this case, different "best"-weapon combinations would be chosen, in an obvious manner.

All weapons would be deployed peripherally about the target area at a best radius dependent on the weapon characteristics and on the following arbitrary stipulations: The defended area was assumed to have a radius of 2 miles, and it was required that the bomb be killed 10,000 ft outside this area. Furthermore, it was assumed that 10 sec were required for the bomb to die (for the aircraft to fall) after defensive fire was completed. These combined requirements indicate 25,000 ft to be the distance from the target center at which defensive fire must be completed.[a] For all gun systems, this would result in a ringwise emplacement at a radius equal to 25,000 ft plus the maximum effective range of the gun. For the Loki, the high available rate of fire would reduce this requirement and the best emplacement would be at approximately 25,000 ft from the target center. The automatic barrage rockets would, of course, be placed on the 25,000-ft-radius circle.

IV. Weapon Effectiveness

The over-all weapon effectiveness, calculated according to the gun limitations and operating restrictions given above, is summarized in Table 24 for

[a] This result varies with bomber speed and was computed for the case of TU-4. With the advent of faster bombers or faster air-to-surface missiles, the weapon deployment will be farther from the target center and consequently more costly.

the various assumed altitude-profile-visibility conditions for defense against a TU-4 bomber attack.

Table 24

WEAPON EFFECTIVENESS AGAINST A TU-4 BOMBER ATTACK

Conditions	Weapon Effectiveness: 40 mm or T-131	Skysweeper or Loki	Automatic Barrage Rockets	Terrier I
1. 200-ft daylight attack with zoom to 2000 ft over target	Fully effective	Reduced effectiveness	Fully effective	Ineffective
2. 1500-ft night attack	Possibly effective (with visual aids)	Fully effective	Fully effective	May be effective

Table 24 indicates that a combination of local-defense weapons will have to be employed to maintain effectiveness under all conditions of attack. Typical combinations may be as follows:

1. 40-mm guns plus Skysweeper or Loki (in 1953).
2. T-131 plus Skysweeper or Loki plus Nike or Terrier I (in 1955).
3. T-131 plus Nike or Terrier I (in 1955), provided visual aids are developed to extend the T-131 to nighttime operation, and provided the guided-missile performance can be extended downward to around 5000 ft.
4. The automatic barrage rocket plus the advanced Terrier-type (in 1957).

The kill probabilities of each weapon have been determined for those attacks for which it is fully effective. Tables 25 and 26 were calculated for 200-ft attacks against 40-mm and T-131 guns and for 1500-ft attacks against Skysweeper and Loki. These values are actually representative over a fairly wide range of attack altitudes.

Since the enemy may approach from any direction, there is a certain minimum number of peripheral guns (designated g_0 in the following equations) needed to ensure that the enemy will be attacked by at least one gun. In such a minimum arrangement, there would be a certain gunfire overlap which would vary somewhat with the altitude of the attacking bombers. Assuming that this minimum number of guns is employed, the effectiveness of these local-defense

weapons has been expressed in terms of expected killing hits against various aircraft targets. The results are given in Table 25, together with the assumed minimum number of units. The aircraft vulnerable areas which were assumed in the computation of Table 25 are indicated in Table 26.

Table 25

EXPECTED KILLING HITS (E_k) AGAINST A SINGLE AIRCRAFT ATTACKING A MINIMUM DEFENSE INSTALLATION

(Defended area radius = 2 miles; no operational degradation factors are included)

Weapon*	Number of Mounts in Minimum Installation	Expected Killing Hits Against					
		TU-4	Stalin	Lenin	Subsonic Air-to-Surface Missile	Supersonic Air-to-Surface Missile	V-1 Missile
Automatic gun, Quad 40 mm	14	1.11	1.28	.401	.603	.201	1.46
T-131	14	6.85	8.33	2.47	.466	.155	1.13
Skysweeper	4	1.21	1.80	.499	.313	0	.625
Loki battery	4	7.00	10.4	2.89	.184	.0611	.428

* Automatic barrage rockets are treated separately because of the different nature of their cost and kill relations.

Table 26

VULNERABLE AREAS OF THE VARIOUS BOMB CARRIERS

(Square feet)

Weapon	Vulnerable Area of					
	TU-4	Stalin	Lenin	Subsonic Air-to-Surface Missile	Supersonic Air-to-Surface Missile	V-1 Missile
Automatic gun, 40-mm	65	108	65	75	75	120
T-131	520	910	520	75	75	120
Skysweeper	1400	3000	1600	10*	10*	10*
Loki	1400	3000	1600	78	78	120

* VT-fuze fragmenting round.

The percentage of the bomber force killed in attacks against any of these weapons is given by:

Per cent attrition $= 100\left[1 - \exp\left(-\frac{g}{g_o}\frac{E_k}{K_f}\right)\right]$ if one or more guns bear on each aircraft; i.e., if $\frac{g}{g_o K_f} \geq 1$,

Per cent attrition $= 100 \frac{g}{g_0 K_f} [1 - \exp(-E_h)]$ if less than one gun bears on each aircraft; i.e., if $\frac{g}{g_0 K_f} < 1$,

where $g =$ the number of mounts deployed around the target area,

$g_0 =$ the number of mounts in a minimum installation (see Table 25),

$E_h =$ the expected killing hits per minimum installation (from Table 25),

$K_f =$ the number of aircraft targets in a tight formation coming over the gun essentially simultaneously. This means that in the case of the 40-mm and T-131 guns, a "tight formation" must have a width and length of less than 2 miles, whereas in the case of Skysweeper and Loki, it could be about 3 miles.

V. Degradation

The co-ordinated action of many people is required for the successful operation of guns. An analysis of World War II data and postwar proving-ground data indicates that confusion is the principal source of degradation. For radar-directed guns, the operation and maintenance of the radar is another important source of inferior performance. Based on World War II experience, it was assumed that against nonmaneuvering targets, the number of guns (g) for all weapons should be degraded by a factor of 3. A degradation to account for the effect of maneuvering[7] will be dependent on the time-of-flight of the shell and therefore on the target altitude, and should be applied to the expected killing hits (E_h). Specific factors to account for maneuver at various altitudes and for other degradation affecting the expected killing hits were assumed to be as follows for the various weapons:

Weapon	Target Altitude (ft)	Maneuver Degradation Factor
Automatic gun, 40 mm	2000	1.2
T-131	2000	1.4
Skysweeper	5000	3
Loki	5000	3

The maneuver degradation should be applied only if the attacker is given

credit for being able to maneuver during the bomb run at low altitude. Considering the problems of formation flying, low-altitude bomb delivery and crew escape, and evasive action during the bomb run, it seems rather unlikely that the offense will be able to do *all* of these things correctly in a low-altitude attack within the time period of the present study. For this reason, the degradation factors are enumerated and the assumptions discussed above. Degradation due to failure of the entire weapon system (e.g., failure of the early warning) would apply directly to the final kill potential. However, this factor is discussed separately and is not included in the numerical calculations.

VI. Costs and Manning

Information on the cost of the various weapons (except the T-131 rocket gun and the automatic barrage rocket) was available from Army sources. The costs of the T-131 rocket gun and automatic barrage rocket were estimated by assuming an organization and then costing the components. The associated men-and-equipment requirements were deduced from conventional Army structures by eliminating those items pertinent to a mobile structure but believed to be unnecessary for the defense of the United States and incorporating the functions pertinent to the operation of a semi-permanent installation.

In costing some of these local-defense weapon systems, a new possibility emerged which had not been considered in costing interceptor, radar, or missile defenses. Some of these weapons, particularly the smaller-caliber guns and the automatic barrage rockets, seemed simple enough to be manned in part by trained civilian volunteers in a time of dire national emergency. For such weapons, this would reduce the cost of a given capability or increase the defense strength for a given budget. Costs of these weapons are shown with and without the assumption of civilian manning in Table 27.

VII. Comparison of Weapons

The costs given in Table 27 can be combined with the kill-probability estimates of Table 25 to obtain a comparison in terms of expected killing hits per million dollars of annual budget, as was done in the case of the local-defense guided missiles. Typical results for the defense of a circle of 2-mile radius are shown in Table 28.

Table 27

COST SUMMARY FOR LOW-ALTITUDE DEFENSES

(Millions of dollars)

Weapon	Initial Cost per Mount	Annual Cost per Mount	Effective Annual Cost per Mount*
Automatic gun, quad 40 mm	.298	.196	.270 (.185)†
T-131	.217	.158	.212 (.157)†
Skysweeper	.676	.293	.462
Loki	2.150	1.068	1.606

* Effective annual cost is defined as the annual cost plus 25 per cent of the initial cost.

† Figures in parentheses are modified costs for organizations employing civilian volunteers.

Table 28

EXPECTED KILLING HITS PER MILLION-DOLLAR ANNUAL EXPENDITURE

Weapon	TU-4 (No Evasion)	TU-4 (With Evasion)	Stalin (No Evasion)	Lenin (No Evasion)	Subsonic Air-to-Surface Missile	Supersonic Air-to-Surface Missile	V-1 Missile
				All-Military Manning			
Automatic gun, quad 40 mm	.098	.082	.113	.035	.053	.018	.129
T-131	.769	.549	.935	.277	.052	.017	.127
Skysweeper	.218	.073	.325	.090	.056	0	.113
Loki	.363	.121	.540	.150	.010	.003	.022
				Part-Volunteer Manning			
Automatic gun, quad 40 mm	.143	.120	.165	.051	.077	.026	.188
T-131	1.04	.741	1.26	.374	.070	.023	.171

Although many of the targets considered in the present study are isolated "point" targets, to which the preceding results can be applied directly, there are also clusters of point targets and area targets to be considered. The cost of obtaining a kill in such a case depends on how the weapons are deployed and on how the targets are attacked. If the bombers were capable of formations tight enough so that all the desired bombers were over one gun at one time, it would be proper to deploy the weapons in concentric rings or crisscrossing patterns over the target area, and the expected kills per unit cost would be

about the same as if the target were broken up into a number of point targets equal to the number of aiming points in the target area. If, on the other hand, the bombers were not capable of flying tight formations over the guns, it would be proper to deploy the weapons in a ring around the edge of the target area; the defenses would then be stronger than if the targets were isolated.

The unorthodox automatic-barrage-rocket defense, mentioned earlier, has been suggested in an attempt to obtain a cheap and effective low-altitude defense simple enough to be produced and installed quickly. Such a defense system has been studied in some detail and some of its design characteristics have been chosen. This has permitted cost and effectiveness estimates to be made.

The proposed rocket is an unguided contact-fuzed weapon using single-stage propulsion. The cost and kill calculations were based on a 23-lb gross weight, 2.2-lb warhead, and 7-lb propellant weight. The length could be about 3 ft and the diameter, 3 in.

For comparison with the previous weapons, a "point"-target defense has been considered in which these rockets would be deployed approximately 25,000 ft from the target, giving a perimeter of about 150,000 ft. Electronic fuzes would be installed at about 1000-ft intervals along the perimeter. The economy of this weapon system lies in the fact that the rockets would be left in place and would require very little attention until an attack came, and even then no aiming mechanism or gun crews would be required. One or more 1000-ft sections of the rocket perimeter would be fired automatically when an aircraft flew into the beam pattern of the electronic fuze. (See Fig. 66.)

For an automatic-barrage-rocket system, designed to operate against aircraft at 1500 ft, the relation between the expected kill (P_K) on a single TU-4 bomber and the number of rockets per foot of perimeter (N_p) is roughly approximated as:*

$$P_K = 1 - \exp(-4.7N_p).$$

For a system designed for operation at 1500 ft, but actually operating against targets at 200 ft, the expected kill is increased considerably and may be approximated as:

$$P_K = 1 - \exp(-12N_p).$$

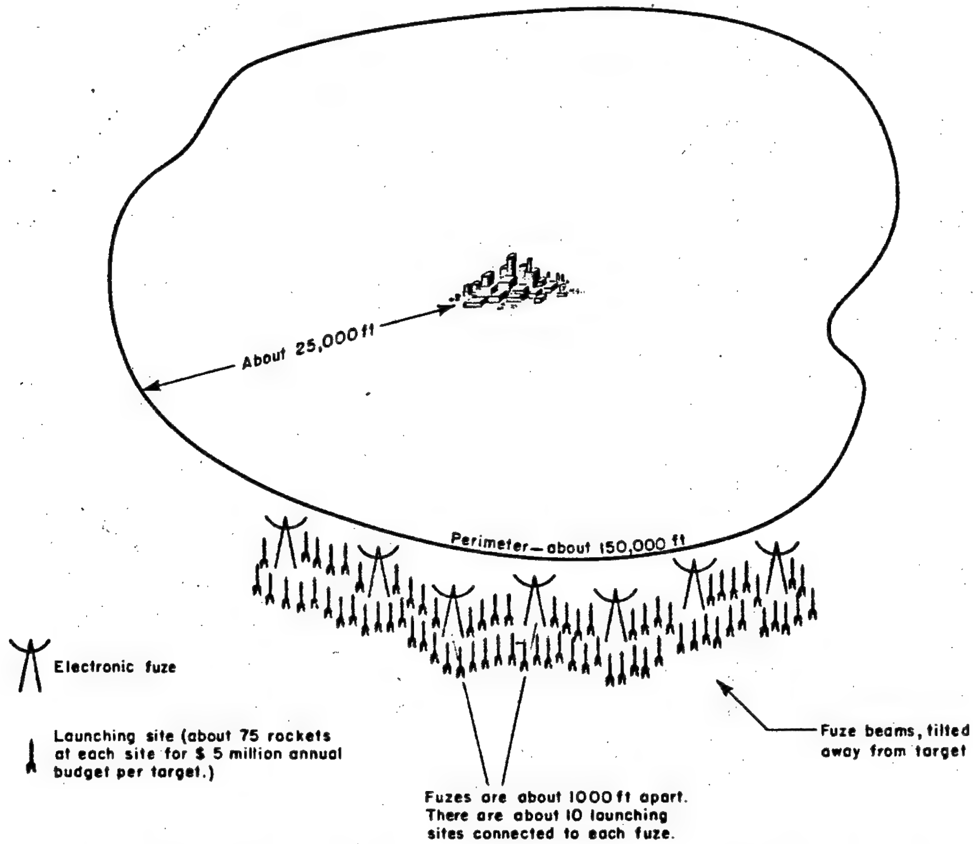


Fig. 66—Schematic layout of a possible deployment of automatic barrage rockets

To account for operational degradation, it is estimated that N_p should be divided by a factor of 2.

If the bombers could attack in train, separated laterally by not more than 1000 ft, and it is assumed here that they could, then it would be necessary to have more than one salvo of rockets ready for firing, and the electronic fuzes would have to be designed to trigger successive salvos of rockets at targets crossing the barrier successively. The number of salvos (S_a) which should be available would depend on the defense level, as well as on the enemy tactics estimated. This relationship is discussed in Part II. The effective annual cost for an automatic-barrage-rocket system for a 150,000-ft perimeter can be ex-

pressed in terms of the number of rockets per foot per salvo (N_p) and the number of salvos available (S_a) as follows:

Effective annual cost,

Millions of dollars $= 1.11 + 5.23 S_a N_p$ (manned by military personnel),

or

Millions of dollars $= 0.82 + 3.88 S_a N_p$ (manning augmented by civilian volunteers).

VIII. Kill Potentials per Target for Unguided Weapons

Kill potentials[9] of guns and other unguided weapons were computed *per target* for a given annual defense budget per target. For all of these weapons, except the automatic barrage rockets, the computations were based on the values given in Table 25 (page 226) for expected killing hits (E_h).

In some cases the logical actual employment of a gun would be to divide its fire among two or more enemies. This would be done if undivided fire resulted in "overkilling" the enemy. In calculating the kill potentials of the T-131 and Loki weapons firing at TU-4, Stalin, or Lenin bombers, it was estimated that the average division of fire would be between two enemy carriers. It was estimated that either weapon would be idle for 25 per cent of the time while switching from one bomber to the other. No division of fire was estimated for other weapons, or for any weapon when the enemy was assumed to use a V-1 missile or an air-to-surface missile. After estimating the division of fire to be 1:2, the values of E_h from Table 25 were divided by 2 and multiplied by 0.75 to allow for idle time; the kill potentials were then multiplied by 2, since kills would be made independently on two bombers.

Kill potentials per target for the weapons listed in Table 25 were found by the following relation, which was adapted from the attrition equations given previously:

$$\left.\begin{array}{l}\text{Kill potential per target for}\\ \text{\$5 million annual defense budget}\\ \text{per target}\end{array}\right\} = \left(\frac{5 \times 10^6}{C_m}\right)\left[\frac{1 - \exp\left(-\frac{E_h}{D_1}\right)}{g_0}\right].$$

[9] For a definition and discussion of kill potential, see Chap. 7, page 126.

The expected killing hits (E_h) and the number of mounts (g_0) are taken from Table 25. D_1 is a combined degradation factor, being the product of the factor of 3 and the maneuver degradations (if applicable) discussed on page 227. C_m is the effective annual cost per mount from Table 27.

To calculate the kill potential of the automatic barrage rockets, the first step is to find the value of $S_a N_p$, the number of rockets per foot in all salvos, for a \$5 million annual effective cost; this is accomplished by using the relation given on page 232. Next, the expected kill (P_K) is found for the given value of S_a, for which the system is designed, by using the equations on page 230 and dividing N_p by the degration factor of 2. Finally, the kill potential per target is found by multiplying P_K and S_a. Appropriate values for S_a depend on enemy tactics and defense level. A value of eight salvos was taken for the kill-potential computations of this chapter.

The resulting kill potentials against TU-4 bombers, Stalin bombers, and V-1–type missiles are shown in Figs. 67, 68, and 69 (pages 234 through 236). These graphs are based on all-military manning. The automatic barrage rockets were *designed* for 1500 ft attack in both cases shown on each figure.

Numerical values of kill potential for the rather dissimilar weapons discussed in this chapter can be very misleading if considered out of the context of the assumptions used in their computation. The use made of the kill potentials should determine the exact rules used in computing them, since several interpretations can be made of the basic concept of kill potential. This is particularly true of the assumptions about division of fire and, in the case of automatic barrage rockets, the number of salvos.

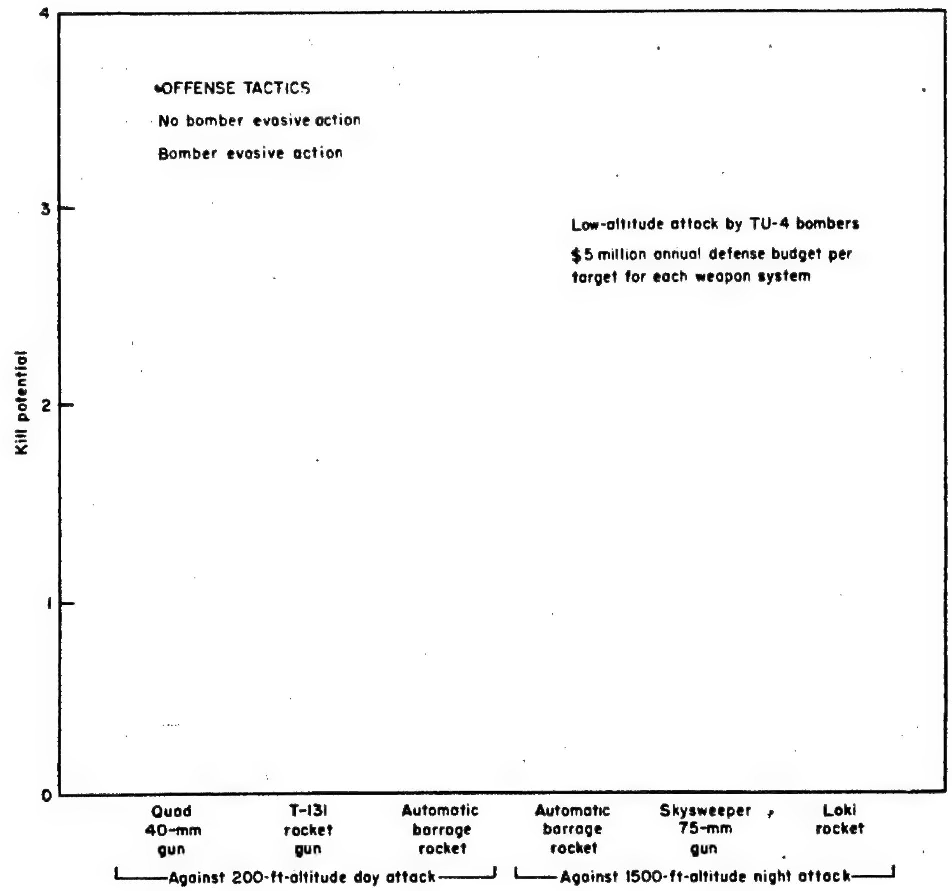


Fig. 67—Local-defense gun and rocket effectiveness against TU-4 bombers

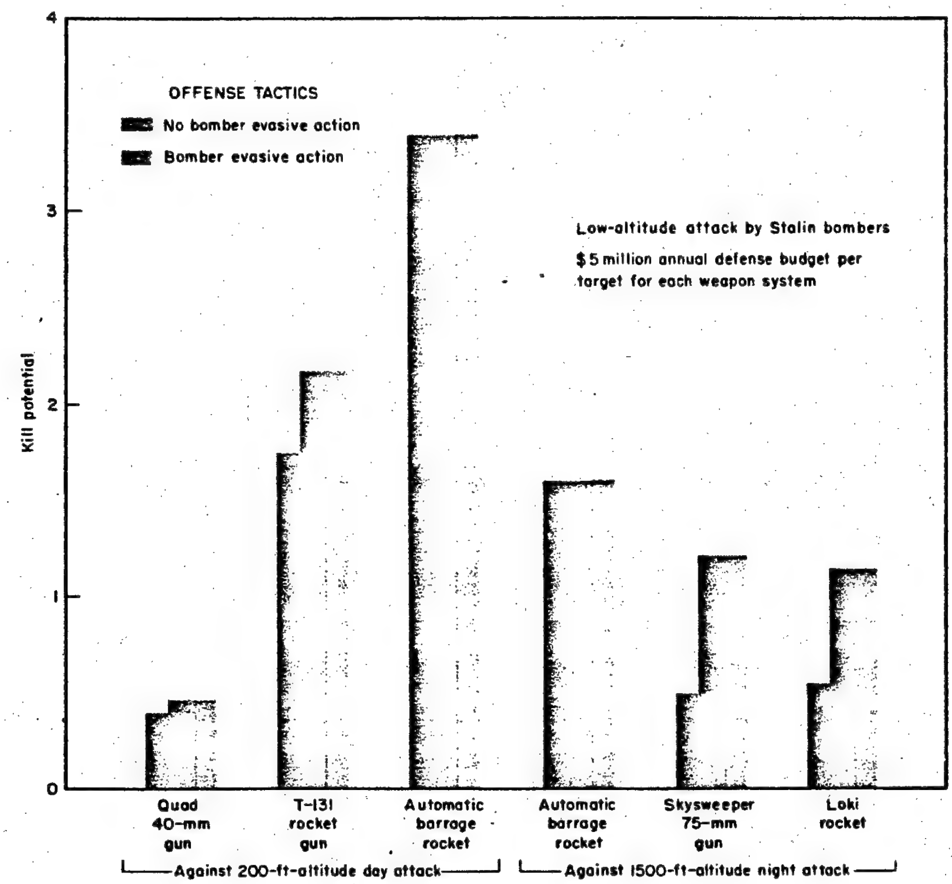


Fig. 68—Local-defense gun and rocket effectiveness against Stalin bombers

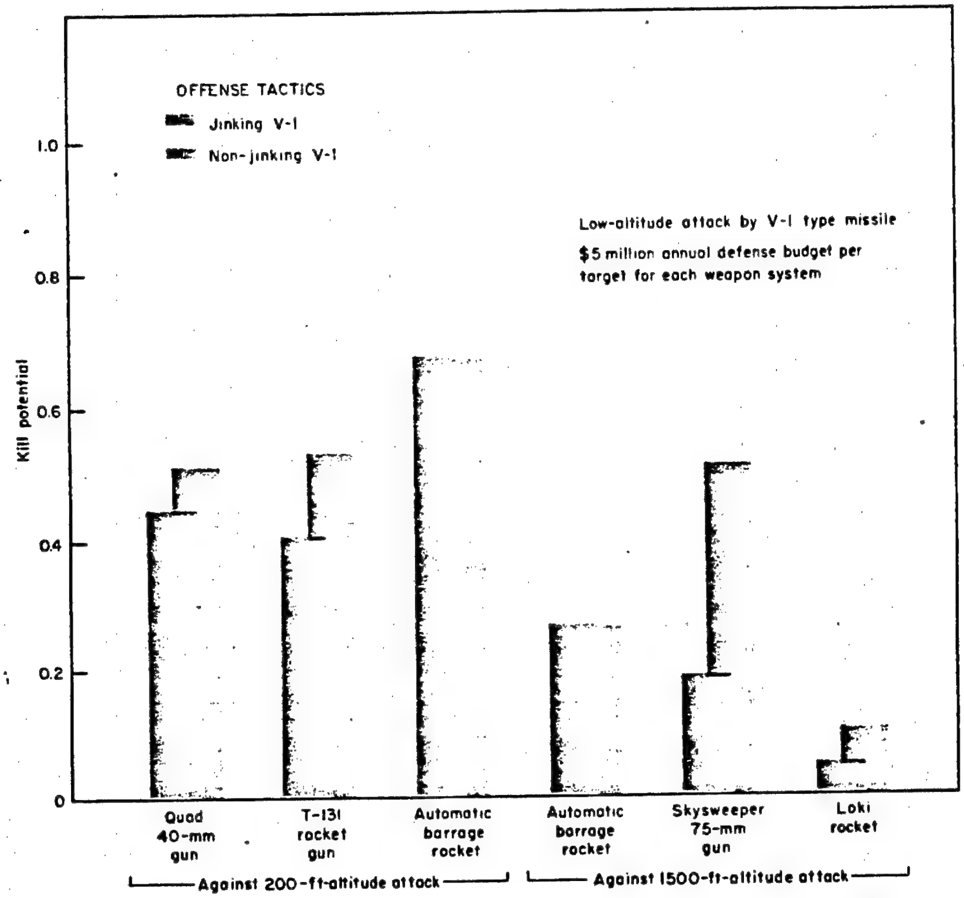


Fig. 69—Local-defense gun and rocket effectiveness against V-1–type missiles

CHAPTER 11
RADAR NETWORKS

I. Problems of Planning and Building Radar Networks

The United States is now building a radar network of unprecedented extent and complexity, and even more ambitious proposals are currently under consideration. The network in the United Kingdom, in spite of its evolution under operational conditions, is far from adequate in providing our own planners with the lessons of experience, for the British have not yet installed many microwave radars and they place great reliance on a well-organized Royal Observer Corps. The fact is that there is a dearth of experience to guide this effort. The exigencies of the world situation, however, have forced the United States into a full-scale program of radar-network construction.

Unforeseen difficulties, therefore, are to be expected. There is a distinct need for careful planning, both military and scientific. There will necessarily be many changes in plans and procedures as operational experience accumulates. Realistic exercises should play an important part in this learning process.

It is characteristic that air defense operations in the United States, by their very nature, require an extensive and complex network of data-gathering and data-processing facilities. The interdependence of the sources of our war-making potential precludes the concentration of defense forces at a few prime targets (the target list discussed in Chap. 4 has about 500 targets). Furthermore, the initiative in strategic bombing lies with the offense. Thus, in order to get into the engagement the largest possible fraction of defense weapons, uniformly allocated over the pattern of attack chosen by the enemy, our defense forces must rely on our radar network.

FLEXIBILITY TO MEET THE UNEXPECTED

There is an important and frequently overlooked point: *Taking advantage of unexpected enemy weaknesses may be decisive in a military operation, and the radar network enables the defense commander to do this.* Advance planning of defensive operations characteristically ascribes to the offense more capability in each of several respects than it is likely to have in *all* of these respects. As an

attack develops, a defense commander, who has an accurate picture and efficient communications, can exploit enemy weaknesses as they are revealed. When the difficulty in achieving practical operation with some of the presently proposed weapons is considered, it appears that our defense will be inadequate, in many of the years covered by RAND's Air Defense Study, unless it does take advantage of enemy blunders and weaknesses.

NATURE OF RAND'S RADAR NETWORKS STUDY

RAND's study of radar networks is described in this chapter. Most of the discussion is closely tied into the sequence of defense actions for which the radar network provides information. These actions include the detection of enemy bombers (and the subsequent tracking of their flight), their identification as enemies, the allocation and assignment of defensive forces, the control of weapons, and sometimes the recovery of the weapons. These subjects are treated more or less in turn. In addition, there is discussion of the extent of coverage required to perform these actions and some data are given on the costs of various types of networks. The allocation and assignment of weapons is considered toward the end of the chapter, where lateral deployment of area-defense weapons and protection against enemy feints are discussed briefly.

Area-defense weapons generally impose more stringent requirements on the design of radar networks than do local-defense weapons. Although the majority of local-defense-weapon systems will receive data from the main radar network up to the assignment phase, most of the specialized guidance needs of local-defense weapons will not come from the network, but from an individual local-guidance unit. These problems are treated in connection with the weapons discussed in Chaps. 9 and 10. Among area-defense weapons, the various interceptors will probably predominate during the time period studied. Hence, most of the study of radar networks was in terms of interceptor systems. Extensions to include area-defense-missile radar requirements were made when necessary.

The basic target list, which includes about 500 targets, permitted a new type of statistical study to be made of the effectiveness of networks varying in extent. It was therefore unnecessary to use the concept of defending a "heartland" surrounded by a belt of radar, as in previous studies. Another characteristic of the study was the attempt to use probability distributions rather than expected values when it appeared that the results would be significantly improved. A third technique, not fully exploited in the study, is the construction

of a mathematical or graphical model which bears a very close analogy to the physical situation; this technique was useful in studying the performance of very complex systems, such as the radar network. In conjunction with this model, it may also be advantageous to employ random numbers in connection with probability distributions of enemy tactics, or of some network parameters, in determining the spread of performance to be expected of the network.

In describing the radar network study, convenience has necessitated a rather arbitrary selection of certain definitions and assumptions. This was unavoidable because the idea of a big radar network in the United States is so new that as yet there is no fixed usage of terms. Two specific definitions might be mentioned here. "Gap filler" has some current usage as a mobile GCI of the AN/MPS-7 type; in this report it refers to a small radar of the AN/TPS-1D type, used for low-altitude coverage. The old term, ADC (air direction center), is currently being replaced by ADDC (air defense direction center). In this report, ADDC is used only for stations of the AN/CPS-6B cost class, and GCI is used for AN/FPS-3's (although this usage of these terms is not necessarily a generally accepted one).

DATA GATHERING BY MEANS OTHER THAN CONVENTIONAL RADAR

There are many ways of obtaining information on enemy bomber movements other than by the use of conventional radar. Some of these are as follows: high-frequency (3- to 30-Mc) ground-wave radar, ionospheric radar, the use of tropospheric propagation, the detection of electrostatic discontinuities, passive direction finding on enemy propagations, acoustic devices (particularly in the Arctic or in conjunction with submarine-detection networks), intelligence information, Y-service (monitoring enemy communications), and the Ground Observer Corps.

Except for the ground observers, none of these methods has been given extensive operational implementation so far. Some are still quite experimental, others are of doubtful or specialized operational utility, and still others will provide only special supplementary data. In RAND's Air Defense Study, note was taken of these techniques in arriving at the conclusions of the study, but little detailed investigation was made, except for a modest study of ground observers, and no numerical calculations were carried out.

II. Summary of RAND's Studies of Radar Networks

The studies of radar networks have dealt with several major topics: the performance of radars and networks of radars, the relation of network geographical extent to defense-weapon utilization, the cost of networks, and the technical feasibility of various schemes and equipments. These studies were made to yield quantitative answers to the extent that time permitted.

THE QUALITY OF NETWORK PERFORMANCE

As an essential preliminary to some of the interceptor air battle and surface-to-air missile studies, as well as to the selection of the most promising equipments to consider in an economic sense, it was necessary to evaluate the performance characteristics of radars and networks. Five classes of characteristics are discussed in brief here; they are described in greater detail later in this chapter.

Detection

The probability that each of the enemy targets would be detected by the various radar systems likely to exist during the time period of the study was investigated; the results are reported in Secs. III and IV, pages 245 through 266. This investigation involved estimates of expected proving-ground performance of these radars and, in addition, consideration of the questions of maintenance degradation in field performance and operator attention factor. These estimates were made on theoretical grounds. It would have been preferable to use field measurements, but there were not sufficient data available on most radars when the study was being made.

Traffic Capacity of the Radar Network

The network must be capable of handling routine air traffic and the unusual military traffic, and still be able to identify and track hostile aircraft. It is important in considering the traffic-handling capacity of a network to distinguish between two types of traffic: that entering the boundaries of the Zone of the Interior (ZI)—this traffic is relatively light for almost all approaches—and that within the interior—this traffic is much heavier in some locations, being extremely heavy in some cases, because of the high load of routine air traffic. This topic is discussed in Sec. V, pages 266 through 275.

Identification Capability

Once the information on the air situation has been gathered, filtered, and dispatched to its users, the next step is to try to identify all unknown tracks in the search for hostile targets. Several identification procedures have been considered and investigated, and an attempt has been made to estimate the effectiveness which we can expect in the identification process. The most effective process would involve a series of operations, such as flight-plan identification, check-point investigation, use of electronic IFF equipment, and diversionary landings. Identification is discussed in Sec. VI, pages 276 and 277.

Control Capacity

After aircraft have been identified as hostile, and the routine traffic has been possibly cleared away, the scene can be set for an air battle between the bombers and the friendly interceptor force. At this point the question of interest is, How many interceptors and bombers can the ground network control? This question depends on the type of control used and, to a great extent, on the time period for which the question is posed. Some study has been made of this problem and some estimates are given for the expected control capacity required and obtainable under various conditions. (See Sec. VII, pages 277 through 283.)

Tracking Accuracy and Continuity

The ability of the network to give continuous and accurate tracking information on enemy bombers and on friendly interceptors or guided missiles was studied. The requirement for continuity is one of the factors that determine the power and spacing of radars. The accuracy of tracking must be estimated in order to evaluate the requirements for airborne intercept (AI) radar and to evaluate the likelihood of successful interception by our defense weapons. Estimates have been made of the tracking or vectoring accuracy of the network over the time period of the study, consideration being given to various possible kinds of ground equipment. This is discussed in Chaps. 7 and 8. The probability that the data are continuous is discussed in Sec. IV (pages 255 through 266) of this chapter.

RADAR COVERAGE EXTENT: ITS DEFINITION AND MEASUREMENT

Since the enemy must travel through different depths of radar coverage on his way to different targets, and since radar detection is by nature a statistical

process, it is necessary to measure the extent of radar coverage statistically. One set of statistics was obtained by laying out on a map the target system described in Chap. 4 and superimposing various possible combinations of ground and overocean radar networks. The distances through radar coverage which enemy bombers must fly to various targets were tabulated in the form of a cumulative frequency curve. It was then possible to characterize any given radar network by a distance which was called the "cover." Cover is defined as the radar penetration distance which is equaled or exceeded by all but a certain percentage (say, 5 per cent) of targets. This measure of effectiveness is used in several of the charts in this chapter. (See Sec. VIII, pages 283 through 289.)

Cover in this sense was always measured for a nominal 100-mile radar range. Corrections were applied when the real radar range was appreciably more or less than 100 miles. In the case of the big ground-based radars, it was important to use another set of statistically measured quantities in obtaining the correction. The initial defense actions—detection, identification, and evaluation of threat—can just begin to take place when the blip/scan ratio of the ground radar reaches about 10 per cent. (Blip/scan ratio is the probability that a given antenna scan will yield a blip on the radar scope.) The prediction of range for a given blip/scan ratio was based on analyses which used estimates of the statistics of operator attention, maintenance condition, and bomber-echoing-area fluctuations, as well as the radar-set specifications. The method of making these predictions is described in Sec. III, pages 245 through 255. In making corrections to the cover numbers when use was made of picket radars or of radars for low-flying raid detection, it was possible to simplify the prediction method just described because many of the statistical variations of range are small compared with the over-all cover distance.

Extent of Coverage in Altitude

Some of the significantly different altitudes at which attacks could be made (from the information-network viewpoint) are listed below:

1. By day, one-way attacks could be made by TU-4 bombers at an altitude as low as 200 ft. Coverage could come from ground observers, airborne early-warning (AEW) airplanes, or very closely spaced surface radars. The economic, organizational, and technological problems of obtaining this coverage may not be overcome in the early years of the study.
2. By night, one-way attacks could be made by TU-4 bombers at an altitude of approximately 1500 ft. There seems to be a good chance of

achieving overland coverage at this altitude by 1954 by one of the means mentioned above, *provided* an energetic program is begun in 1952.

3. The conventional network of AN/FPS-3 and AN/CPS-6B radars begins to give passable coverage above about 5000 ft. Coverage at 30,000 ft, a likely TU-4 attack altitude, is quite good.
4. Attacks by Stalin or Lenin jet bombers (described in Chap. 5) could be made at 40,000 ft. Coverage by the conventional network will be adequate if planned power increases materialize,[1] and if maintenance improves slightly.
5. Long-range air-to-surface missiles could attack at 80,000 to 100,000 ft, and ballistic missiles, at even greater altitudes. These threats impose difficult requirements because of their small echoing areas and high speeds, as well as because of their altitudes. Unfortunately, this study could not consider these threats in very great detail, since the state of the art for the time period concerned is rather uncertain. It does appear, however, that the AN/FPS-7 radar has a capability against 100,000-ft air-to-surface missiles.

Radar Plans of Varying Geographical Extent

A number of combinations of ground, AEW, and picket-ship radar plans were considered in terms of their geographical extent. Each was the result of experimenting with station locations to achieve the best value of "cover," as well as of considering common-sense siting rules. The 120-site ground network proposed by the Air Force about a year ago was taken as a basic plan. Various increments of ground radar and AEW or picket-ship radars were added, as described in Sec. VIII (pages 283 through 289), where the best combinations and cover numbers are tabulated.

Tactical Usefulness as a Function of Radar Extent

The effect of radar-coverage depth on weapon utilization was considered in three steps: First, in order to obtain a reasonable kill probability, the times, and therefore the radar depths required for all the various defense-system actions, were studied for attacks on the target nearest the defense weapon considered. Secondly, the extra warning times (and network depths) needed for lateral deployment of the weapons were found for cases where more dis-

[1] A 2-Mw offset beam for the AN/CPS-6B and a 5-Mw transmitter for the AN/FPS-3.

tant targets were protected. All area-defense weapons must have such coverage, or they devolve into local-defense weapons. Thirdly, the extra radar required because of possible enemy feints was considered. More radar depth gives the commander the ability to commit a larger fraction of his force against known attacks without being caught out of position by raid elements not yet seen. These requirements are discussed in Sec. X (pages 300 through 306). In addition, there are some special feinting problems in the case of the area-defense missile which arise from its expendability. These are discussed in Chap. 8.

RADAR NETWORK COSTS

A study has been made of the costs of each of the types of radar employed in the present study and of the costs of complete networks of these radars in various combinations. Radars were costed in just the same way as were other items of the study: in terms of their initial costs and their annual operating costs. To obtain a single measure of cost, the initial costs were then prorated over 4 years and combined with the annual cost. Consideration was given to the greater logistic difficulties of installing radars in northern Canada as compared with installing them in the interior of the United States. Six different geographical categories were used in the estimates. Radar coverage over the ocean was also costed for both picket ships and AEW airplanes of several types. In each of these cases, the costs of various back-up factors, auxiliary airplanes, ships, etc., which are necessary to keep a given number of radars on patrol, were estimated. Costs are discussed in Sec. IX (pages 290 through 300).

RADAR FEASIBILITY

In RAND's Air Defense Study, several quite different kinds of radar systems were considered, and problems of the relative technical feasibility of some of these alternative techniques immediately arose. These questions of technical feasibility arose chiefly in connection with (1) the obtaining of low-altitude radar coverage through ground clutter, (2) the tying in of large numbers of radars by means of rapid, effective data handling, and (3) the operation of the air defense direction center and its jobs of handling data, assigning directors, and achieving high control capacity. These questions of technical feasibility were investigated to some extent in the present study; however, since a statement of the assumed costs and availability dates is far from being the whole story, some of these feasibility problems are discussed in Chap. 12.

III. Characteristics of Individual Radars

LARGE GROUND RADARS

During the time period from 1952 until at least 1956, the main ground radars in the defense network will be the AN/CPS-6B and the AN/FPS-3 search radars. The AN/CPS-6B does its own height-finding by means of a combination of vertical and slant beams. The AN/FPS-3 radar needs a separate height-finder, which is expected to be the AN/FPS-6 in most cases. These radars will supply overland cover for attacks by manned bombers at altitudes between those above about 5000 ft and the maximum combat altitude of 35,000 to 40,000 ft.

By about 1956 the next generation of large ground radars might be available to supersede those just mentioned. One such radar, already under development, is the AN/FPS-7, a large multiple-beam radar having integral height-finding; this radar will give a better range performance than the preceding ones. (It may require a separate height-finder when used against targets in its bottom beam, however.) A network of these radars, if sited as the present network is sited, would have the same low-altitude limitation of about 5000 ft but would give better high-altitude coverage. However, by this time period it is possible that a requirement will exist for defense against high-altitude air-to-surface missiles or long-range surface-to-surface missiles. The AN/FPS-7 radar might not be adequate against such advanced threats. Therefore, there is a need for a study of the proper type of ground radar to supersede the AN/CPS-6B and AN/FPS-3 radars (or the AN/FPS-7); this radar should be available during the time when such defense missiles as Bomarc are intercepting high-performance offensive missiles. The present Air Defense Study has not reached any conclusion or recommendation about the large ground radars of this period. It has been assumed that the AN/FPS-7 radar or something similar would be adequate for use by Bomarc I missiles against high-speed bombers, or against air-to-surface missiles if they do not fly too high. Work is continuing at RAND, however, on the problem of both the weapon and radar requirements for defense against high-performance missile threats. (The all-altitude version of Muldar, which is described below, is another possible kind of radar for this time period.)

GAP FILLERS FOR LOW COVERAGE

During the 1952–1956 period, it might be possible to supplement the radar network with small gap-filler radars to give low-altitude coverage. As an outgrowth of its Air Defense Study, RAND is making a detailed investigation which is intended to help the Air Force to arrive at a firm plan for securing this interim coverage. Such radars might extend the radar coverage down to 200 to 1000 ft and could employ small sets already in production, such as the AN/TPS-1D, the CAA's ASR series, or their military counterparts, the AN/CPN-4 or AN/CPN-18. There are both economic and technical difficulties involved in such a plan. In the present study such a plan was considered, and an estimate was made of the costs of using AN/TPS-1D or ASR radars to achieve such low-altitude coverage. A distinction is made between the use of present techniques of manual filtering at each small radar, employing voice telephone data-telling, called here the "gap-filler" system, and a new technique proposed by RAND which involves automatic data compression and transmission from the small radar to the parent radar, called here the "Encoding Low-Altitude System." The latter method greatly reduces the number of personnel required at each small radar and is therefore much cheaper. This type of radar showed promise of meeting the coverage requirements in recent RAND-sponsored flight tests on the ASR-1.[2] Further work on the design and testing of data-encoding methods and transmission over telephone lines is under way. The question of technical feasibility and the desirability of such a move is discussed in Chap. 12.

MULDAR

The AN/TPS-1D and ASR radars are not the most desirable types with which to obtain low-altitude radar coverage; therefore, it is assumed that a development program will produce a more advanced radar for this application by about 1957, and such a radar network is envisaged for the period of 1957 to 1960. This radar is called "Muldar" and is specially designed for multiple operation with high automaticity. Its performance in a network is discussed in Sec. IV (pages 259 through 261) and its costs are estimated in Sec. IX (pages 295 through 299). As pointed out in Sec. IV, two forms may be considered: low-altitude Muldar and all-altitude Muldar. A design study

has been made of Muldar and some of its preferred characteristics have been deduced. For further details, see Chap. 12.[3]

OVERWATER COVERAGE

For overwater coverage, two general kinds of radars have been considered: picket-ship radars and airborne radars. The picket-ship radars were assumed to have the performance of AN/SPS-6B radars and to be carried by DE(R)'s. These could be available from about 1953 onward throughout the period of the study.[4] In the 1953–1954 period, AEW radars would probably be AN/APS-20A sets installed in Navy airplanes, such as the AD-3 or P2V. By approximately 1954, much more advanced AEW radars might make their appearance through the development of the PO-2W airplane by the Navy. This airplane, a modification of the Constellation, could carry an AN/APS-20B radar having a 17-ft antenna, as contrasted with the 8-ft antenna of the AN/APS-20A radar installed in the AD-3.

Some consideration is being given to the modification of B-29's to carry the AN/APS-20C radar with either an 8-ft or 17-ft antenna. The purpose of such a program would be to obtain an AEW capability with Air Force aircraft before the advent of the PO-2W. At present it appears doubtful that this modification program could become operational before that of the PO-2W. However, cost estimates of such a B-29 AEW program are included in Sec. IX of this chapter.

Another kind of radar which has been suggested for off-shore applications is a high-frequency radar making use of ground-wave propagation to go below the line of sight. As previously mentioned, such radars have not formed an integral part of the present defense study, partly because of the lack of detailed information about their technical possibilities, and partly because their range seems to be limited to about 100 to 150 miles off shore, whereas the requirements of the present study indicate several hundred miles to be more desirable.

COVERAGE OF PRINCIPAL RADARS

In almost all cases specific equipments, now existing or well along in their development, will be available for use during most of the period studied; such

[4] Provided the prerequisite interservice agreements can be worked out.

equipments were considered for the radar-network duties in RAND's study. It is therefore possible to present in this chapter some of the more pertinent characteristics of these sets in typical operational use. The only exception is Muldar; no firm Air Force plans for it existed at the start of the study, and generalized inquiry has been made into the desired radar performance characteristics, as well as into several alternative technical approaches. Suggested characteristics for Muldar are given in Chap. 12.

The pertinent characteristics of the specific radar sets mentioned above are listed in Table 29.[5] Where a choice of values (e.g., of scan rate) is available, only the values used in the calculations described below were listed. The coverage of these radars on *radially approaching* large bombers such as the TU-4 are given in Figs. 70 through 77. A useful way to show this coverage is in terms of the blip/scan ratio. This ratio is the probability that a given antenna scan will yield a blip, or signal, on the radar scope. The graphs are drawn for a blip/scan ratio of 0.5; this means that on the average every other scan will produce a blip. For the antenna-rotation rates used by most of these sets, and for airplane speeds of the near future, a blip/scan ratio of 0.5 is just about adequate for controlling aircraft. These graphs assume the radars to have various departures from perfect maintenance,[6] different bomber altitudes, and different echoing areas. The decibel values noted adjacent to each bar indicate the assumed departure from ideal maintenance. Only the most interesting combinations of bomber type, altitude, and field-maintenance conditions are shown.

Interceptors are not shown in the bar graphs because their echoing areas are so much less than those of bombers that it is planned to equip all USAF interceptors with radar beacons; there will thus be little chance of inadequate coverage.

[6] The maintenance degradations assumed were proving-ground performance, 0 db; most probable, −9 db now and −5 db in the future; worst quarter of radars, −19 db. For the distribution assumed, the most probable value was roughly equal to the average value.

Table 29

CHARACTERISTICS OF RADAR EQUIPMENTS

Radar	Peak Power (Mw)	Beam Width (deg az.)	Beam Width (deg el.)	Gain	Scan Rate (rpm)	Wave-length (cm)	Band-width (Mc)	Pulse Width (μsec)	Repetition Rate (pps)	Maximum Display Range (n mi)	Hits per Scan	Noise Figure (db)	Reference Range* (n mi)	Signal-to-Noise Ratio Required for 0.5 Blip/Scan† (db)
AN/CPS-6B, basic	1	1	fan	10,000	6	10	1	1	600	135	17	13	100	4.7
AN/CPS-6B, 6th beam	2	1	2.8	12,000	6	10	.8	2	300	250	8	10	160	7.5
AN/FPS-3	1	1.3	fan	6,300	6	23	.4	3	400	200	15	9.5	190	5.0
AN/FPS-6	5	3.5	.8	1,300	15	10	1.4	1.5	360	200	8	10	190	7.5
ASR-1	.2	3	csc^2	1,250	26	10	3.3	.5	1,000	60	19	10	20	4.2
AN/FPS-7	10	1.8	2.8	8,000	3	23	.14	7	244	330	24	10	450	3.7
AN/SPS-6B	.5	3.2	30	620	5	23	1	1	600	135	64	13	32	.6
AN/SPS-6B‡	.5	3.2	30	620	5	23	1	4‡	150‡	...	16‡	13	32	5‡
AN/APS-20A, 8-ft dish	2	3	8	1,400	6	10	.8	2	300	...	25	10	56	3.5
AN/APS-20B, 17-ft dish	2	.5	7	2,500	6	10	.8	2	300	...	12	10	83	6.2

* Reference range is the range where the signal-to-noise ratio is 1:1 for a 1-m^2 echoing area and for no integration gain or maintenance degradation. The losses taken as common to all sets in finding reference range were observer loss, 2 db; beam-shape loss, 2 db; plumbing loss, 3 db.

† Integration of all hits was taken into account in computing these values; a fluctuating echo having a Rayleigh amplitude distribution, correlated between hits but not between scans, was assumed. False-alarm time was set to give a 10^{-10} probability of noise exceeding a threshold in any range resolution block.

‡ These values apply to non-MTI operation.

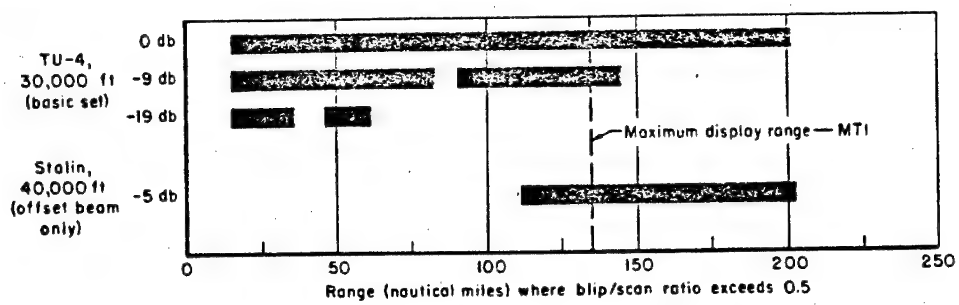


Fig. 70—Coverage of Radar Set AN/CPS-6B

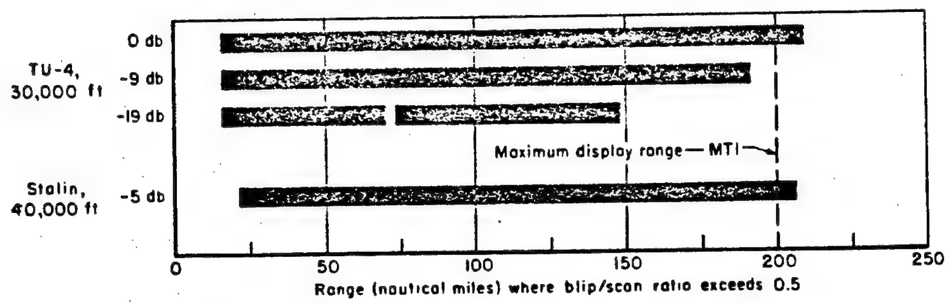


Fig. 71—Coverage of Radar Set AN/FPS-3

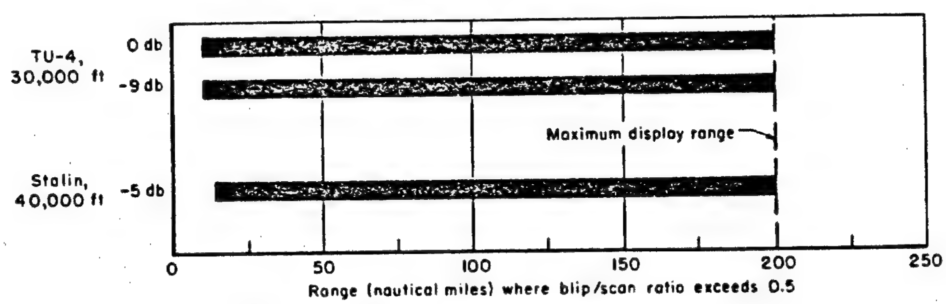


Fig. 72—Coverage of Radar Set AN/FPS-6

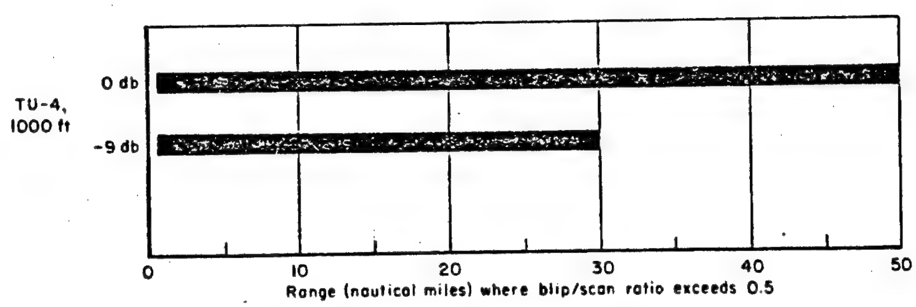


Fig. 73—Coverage of Radar Set ASR-1

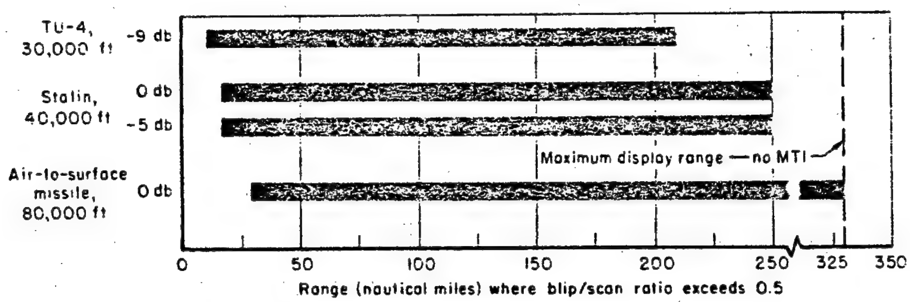


Fig. 74—Coverage of Radar Set AN/FPS-7

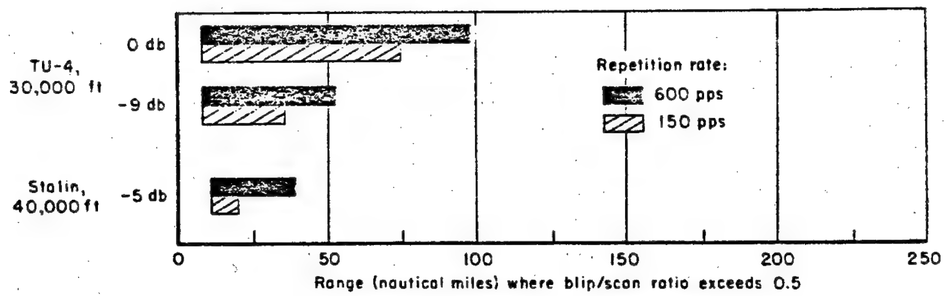


Fig. 75—Coverage of Radar Set AN/SPS-6B

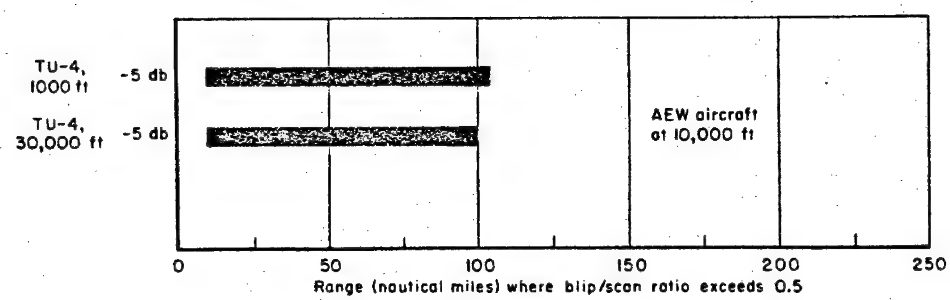


Fig. 76—Coverage of Radar Set AN/APS-20A (8-ft dish)

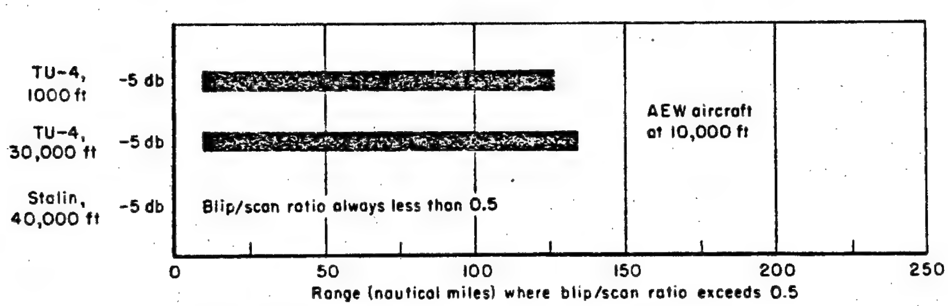


Fig. 77—Coverage of Radar Set AN/APS-20B (17-ft dish)

The graphs were derived by a theoretical method based on the radar range equation.[7] It would actually have been much better to use data from field experience or from flight tests. Unfortunately, there was not very much statistically significant information available when this part of RAND's study was being done, so the theoretical method was used to ensure a fairly uniform comparison of radars.

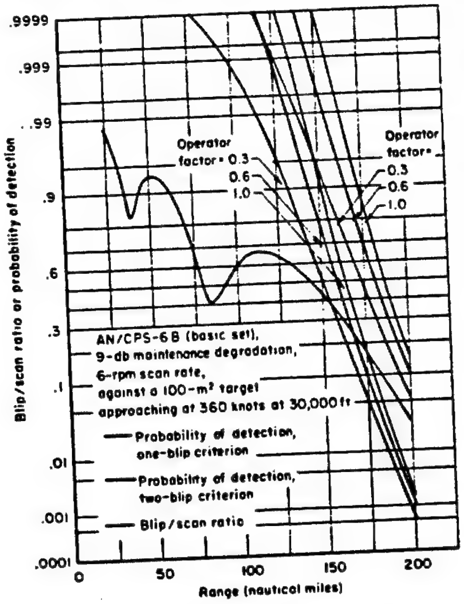


Fig. 78—Comparison of one-blip and two-blip detection criteria

During most of the time while the bombers are within the radar coverage, it is the network's ability to *control* fighters that is of interest. However, there is one necessary function that the radar must perform before control can begin: targets penetrating the radar network must be detected. Whether they realize it or not, the scope operators charged with this job set up a criterion for deciding when a suspected bright spot is a real target blip. Figure 78 shows, as a function of the range of a bomber radially approaching an AN/CPS-6B radar, the blip/scan ratio and the cumulative probability of detection for operators who use either a one-blip criterion or require that two blips appear on successive scans.[8] The operator also sets in a given "false-alarm time," probably by means of a gain control. This false-alarm time refers to the expected time between noise signals that appear to be echoes because they have exceeded a certain threshold.

[7] The graphs are based on the parameters cited in Table 29. Many of the equipments are in the development stage and may not have exactly those characteristics. The computations for Figs. 70 through 77 were made with nomographs prepared by W. B. Graham of The RAND Corporation.

The two-blip criterion results of Fig. 78 are slightly pessimistic. In practice, if the two-blip criterion is used, a somewhat shorter false-alarm time than that used in these calculations would very likely be acceptable, more or less improving the probability of detection. The results for the two-blip criterion would then probably lie between the curves for the two-blip and one-blip criterion of Fig. 78. Both sets of detection curves were derived from the blip/scan curve shown.

Figure 78 also shows the effect of operator inattention. If the operator is busy following other targets, or if he is drowsy or inept, he will not see all the blips that appear. The probability that he will see a blip that is actually on the scope is called the operator factor. Curves are shown for both 1.0 and 0.3 operator factors. Note that the scan rate and the bomber speed are specified in Fig. 78; detection depends on these factors because they affect the number of chances for detection after the bomber enters the region presented on the scope.

MAINTENANCE

It is, of course, extremely difficult to estimate the level of field maintenance to be expected for these radars 5 to 10 years in the future. Only data on the maintenance conditions of radars during World War II are available, as reported by the Radiation Laboratory,[9] and some very fragmentary information on the performance of radars in the air defense network during 1951. The data on World War II experience were very disheartening, since they showed that a large fraction of the radars was maintained below the optimum level by factors as large as 10 to 100 in terms of effective signal-to-noise ratio.

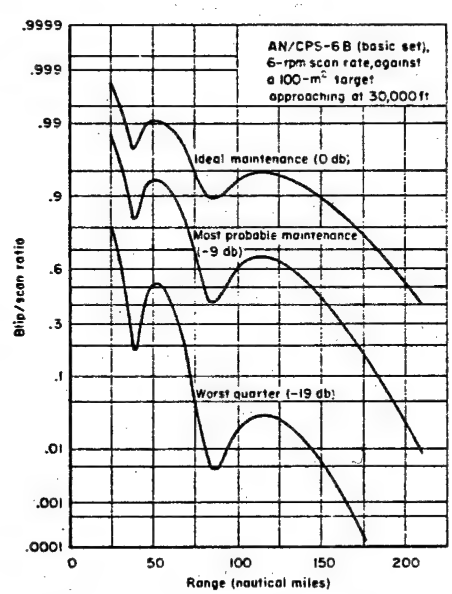


Fig. 79—Effect of maintenance condition on blip/scan ratio

Figure 79 shows the results of applying World War II data directly to the

[9] L. N. Ridenour (ed.), *Radar System Engineering*, Massachusetts Institute of Technology, Radiation Laboratory Series, Vol. 1, McGraw-Hill Book Company, Inc., New York, 1947, p. 592.

air defense radars of this study. In Fig. 79, the blip/scan ratios with and without this maintenance degradation are contrasted for the case of the AN/CPS-6B radar and the TU-4 bomber. In this regard, it is felt that in all probability the maintenance level of the air defense network will be somewhat better in future years than it was during World War II and that the "most probable" curve will then lie between the curves marked "most probable" and "ideal" in Fig. 79. However, to be conservative, the World War II maintenance degradations have been used in evaluating the ground radars in the present study.

GROUND OR SEA CLUTTER

There are special considerations which would modify the curves of Fig. 79 to some extent; these considerations have to do with unwanted echoes from ground clutter or from the ocean. In the case of AEW radar, for example, sea return tends to fill in the central part of the scope, making it difficult or impossible to see nearby targets. The seriousness of this effect depends on the sea state and the AEW altitude, as well as on the equipment parameters. Curves illustrating this effect are shown in Figs. 80 and 81.[10]

Similarly, unwanted ground-clutter signals tend to blank out parts of the scope in the case of ground-based radars, thereby reducing the effective blip/scan ratio in these areas. Moving-target-indicator (MTI) kits are being installed on present ground radars. These kits are similar to the type developed during the war, having a delay line for the comparison of successive pulses during a scan past the target. It is expected that they will considerably alleviate the situation. In the next 5 to 10 years, it is anticipated that much improvement will be made in the field of MTI (there are now promising developments in the laboratory stage), so that these ground-clutter problems will become less serious. Ground clutter is discussed further in Chap. 12 in connection with low-altitude weapons and radars.

This report indicates little correlation between the observed sea return and the Beaufort sea state, but it does indicate that sea return is proportional to the square root of aircraft altitude. The mean standard sea return at 3000 ft for all runs recorded was 44 nautical miles. (Standard sea return was measured with a 70 per cent gain setting, and with no special circuits.)

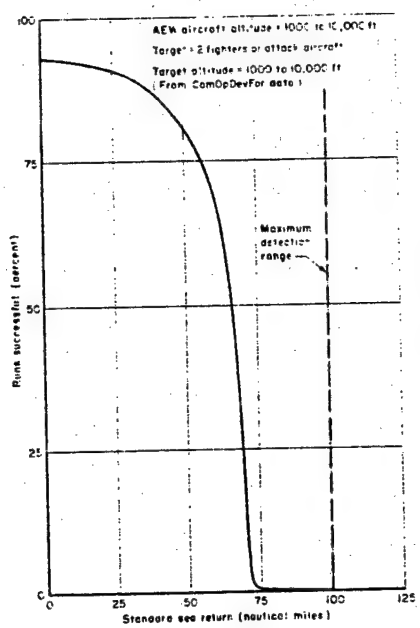


Fig. 80—Percentage of successful AEW runs vs sea state

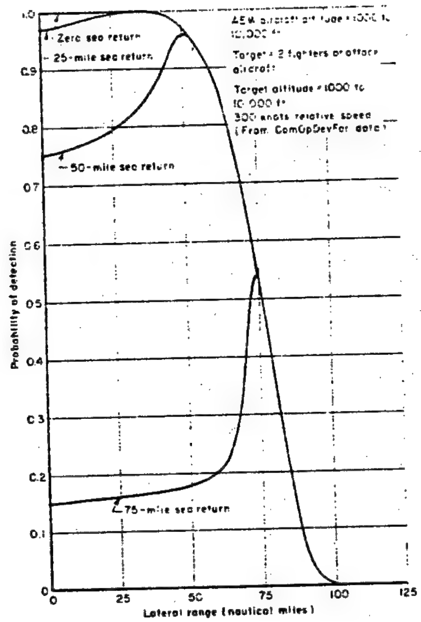


Fig. 81—Probability of detection vs lateral range for AN/APS-20A

IV. Networks of Radars

The over-all performance of a network of radars can be examined in terms of the blip/scan ratio to be expected and the geographical relation of one set to another. The AN/CPS-6B–AN/FPS-3 network of the 1952–1956 period, as planned by the USAF, will be laid out in such a way that the radars will be about 150 miles apart. This means that complete low-altitude coverage will be prevented by the line-of-sight restriction; in addition, there will be a ground-clutter problem. The coverage of this network deteriorates rapidly below about 5000 ft.

HIGH-ALTITUDE LAND COVERAGE

At high altitudes the coverage is limited by the blip/scan ratio to be expected as the bombers pass between the radars. A study was made of a large bomber raid, typical of possible raids attacking East Coast targets and passing

through most of the radars of that part of the network.[11]

The map of Fig. 82 shows the geographical relationship of the assumed targets and bomber tracks. and the planned radars and fighter fields. The raid shown is sufficiently extensive to warrant a certain amount of generalization to other raid tactics and to other targets. The Soviet bombers in the model raid are assumed to attack the 16 leading industrial centers of the Northeast. One bomber section enters from the north and another from the Atlantic; both sections leave by an overland route. (See Fig. 82.) Regardless of the relative probability of one-way and round-trip Soviet bomber missions, it was felt to be permissible to assume the track pattern of a round-trip raid for the purpose of examining radar coverage.

The bombers were assumed to be TU-4's at 30.000 ft and the radars to be AN/FPS-3's and AN/CPS-6B's deployed as planned in the Air Force program. For each of the radars considered in this plan, curves of signal-to-noise ratio were plotted against time for each element of the model TU-4 raid. Examples of these curves are shown in Fig. 83. For each of four equally likely maintenance conditions (−3 db, −7 db, −11 db, and −19 db, identified as *A*, *B*, *C*, and *D* in Fig. 83) these curves were converted to bar graphs showing times when operationally useful data were obtained. Operationally useful data were said to be provided when the blip/scan ratio was 0.5 or better. The first 3 minutes of each run of data was thrown away and runs of less than 15 minutes were discarded because of difficulties in passing tracks and transferring control between stations.

In one part of this study, these radars were assumed to have a maintenance level equal to the most probable value found in the World War II data, and the number of radars simultaneously providing operationally useful data was determined. (This is of interest in considering the sharing of control capacity, for example.) The results were as follows:

Number of Radars Providing Simultaneous Coverage	Percent of Time Bombers Were in Network
One or more	100%
Two or more	77%
Three or more	69%
Four or more	43%

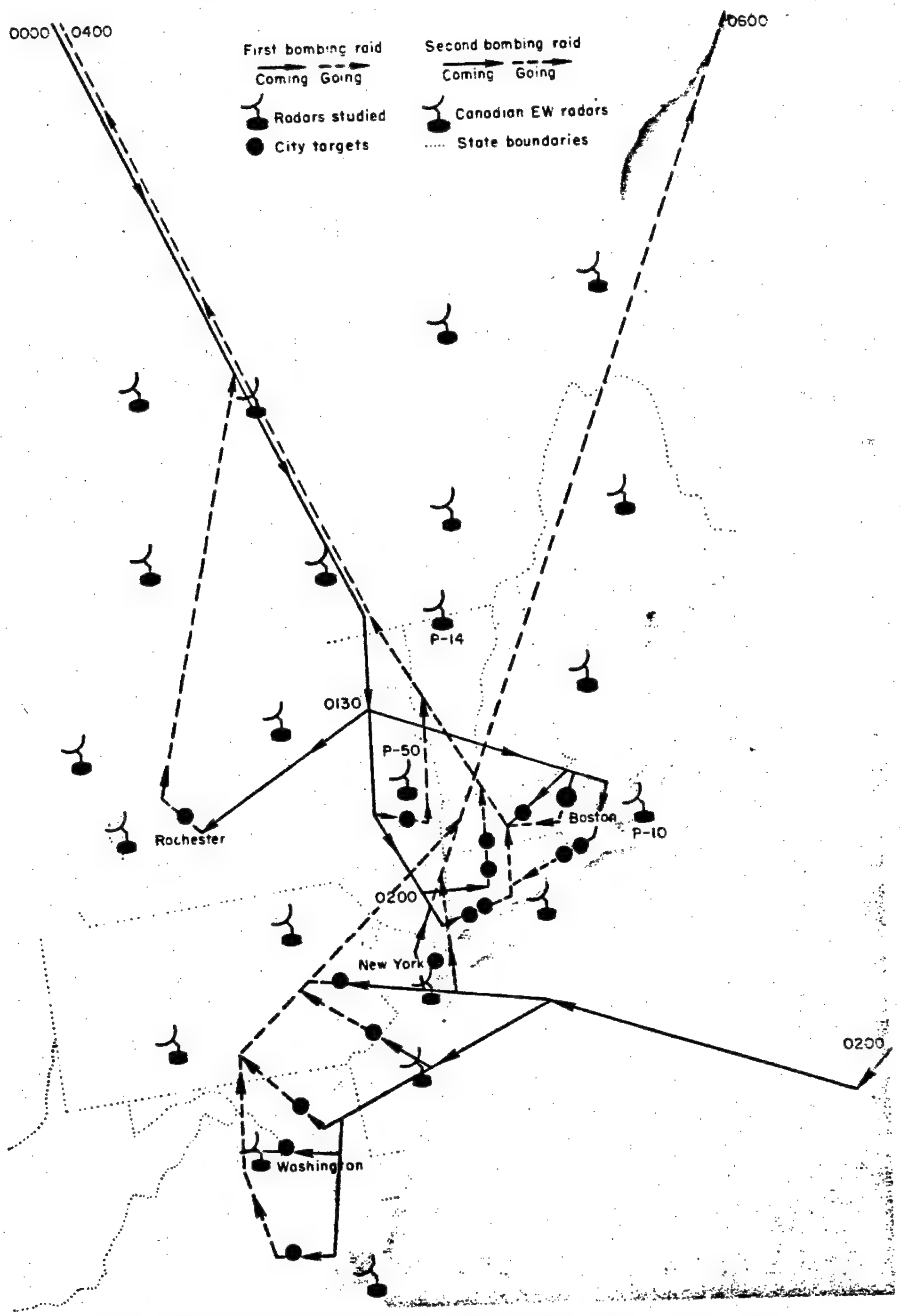
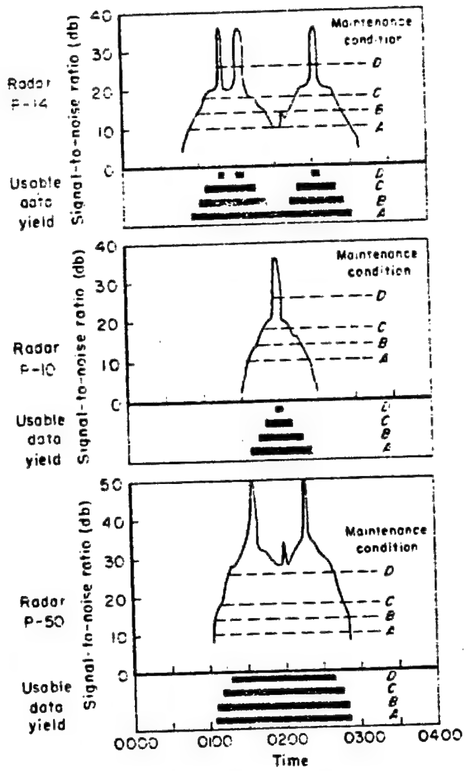


Fig. 82—Model bomber raid on Northeastern United States cities



These curves are for the raid elements attacking Boston. Four equally likely maintenance conditions are indicated by the letters A, B, C, and D; these are degradations of 3, 7, 11, and 19 db, respectively.

Fig. 83—Examples of signal-to-noise curves and usable data graphs

A second part of the study, using the signal-to-noise curves for the same raid, found the probability that useful coverage would be provided by the *single radar* having primary responsibility for the area in which the bombers were flying. A *distribution* of maintenance conditions from the World War II data and the 0.5 blip/scan criterion were used. The results are shown in Table 30.

A third check, in which the same signal-to-noise-ratio curves and maintenance distribution were used, was made to determine the probability of coverage by *any* radar. This probability was so high (being well above 0.99) for all elements of the bomber raid that no numerical results need be quoted.

To make a general statement, these data indicate that against a high-altitude TU-4 raid, where maintenance conditions are no worse than they were in World War II, the planned radar network for the period 1952–1956 will furnish enough data for satisfactory use once the attacking bombers are within the limits of the network. With small improvements in maintenance, and with the planned sixth beam added to the AN/CPS-6B radar, the same statement would apply to the Stalin and Lenin jet bombers in a later time period. The limitations of this network in providing an air-surveillance picture for pre-control actions would then be found in its ability to handle data in the air defense direction centers and in its ability to cross-tell the data from one radar to another. An idea of the effectiveness of the over-all network, including its human operators, is given below (pages 262 through 264).

Table 30

PROBABILITY OF USEFUL COVERAGE BY THE RADAR PRIMARILY RESPONSIBLE

Target Attacked by Bomber Element	Number of Times Bombers Enter New Area of Responsibility	Probability of Coverage by Responsible Radars—Averaged over All of Bomber Track
New York	6	0.82
Philadelphia	8	0.87
Boston	7	0.85
Baltimore	10	0.87
Washington	10	0.87
Providence	7	0.85
Hartford	5	0.95
Rochester	5	0.90
New Haven	6	0.95
Worcester	7	0.85
Allentown	7	0.82
Albany	3	0.92
Richmond	12	0.90

LOW-ALTITUDE LAND COVERAGE: THE MULDAR NETWORK

Three types of ground-based network were studied as possible sources of low-altitude data: (1) a fully manned network of small radars of the AN/TPS-1D type; (2) a network of small radars employing automatic encoding of data and requiring a minimum of operating personnel; and (3) a network of advanced-type closely spaced radars, embodying the results of several years of development. The first type of network was studied largely to obtain an idea of its cost and logistic requirements. The second type was approached from the point of view of finding the best way of using equipment *already developed* to reach an interim solution to the low-altitude problem. This second type is discussed in Chap. 12. The technical problems of the third type, the Muldar network, are also discussed in Chap. 12, but a brief description will be given here, together with enough information to indicate its performance as a network.

Since the Muldar radar is as yet hypothetical, there were no characteristics from which to estimate its performance. Instead the converse was done; i.e., the characteristics (including station spacing) needed to achieve a given network performance were determined. A detailed study was made of the Muldar-type radar relative to the problems of its coverage, scanning time, power require-

ments, expected detection range, etc., to determine if this radar would meet the following primary requirements:[12] First, very complete rejection of ground clutter must be achieved, since this radar is to be used primarily to detect low-flying targets near the ground and since it is proposed to use its output for data-processing devices. Secondly, because a line-of-sight restriction requires that radars such as these be sited very close together to achieve low-altitude coverage, it will take a very large number of them to provide coverage over a large fraction of the United States. This will necessitate the transmission of data from a great number of sets to a few central places. Therefore, one requirement is that the radar be able to process its data in such a way as to permit cheap, narrow-band data transmission back to central places. Thirdly, the radar itself should be cheap to purchase, cheap to maintain, and cheap to operate.

As a result of this study of the problem, it is felt that the most profitable way to attack the ground-clutter-elimination problem in this application is to make use of the doppler principle, to have a highly stabilized transmitter and receiver, and to use tuned-circuit filters to eliminate the ground-clutter echoes. Furthermore, it appears that these systems should be pulse systems, making use of range gates to break the return signals down so that narrow-band filtering techniques can be employed. This will automatically cause the data to be processed in such a way that narrow-band transmission can be employed to get the data back to a central place. One or two ordinary telephone lines should be sufficient to transmit the data automatically from a single radar. This design will eliminate the necessity for operating personnel at the radar itself; only maintenance men will be required.

ALL-ALTITUDE MULDAR

Since the range requirement on any one of these sets is small, because of the close spacing, it is easy to obtain enough power to ensure a very high blip/scan ratio for the desired targets. Two general types of coverage were considered for these radars: (1) a low-altitude Muldar, which would cover up to about 5000 to 10,000 ft and out to about 25 miles and would supply no height information; and (2) an all-altitude Muldar, which, while covering out to 25 miles, would also attempt to cover up to the highest altitude at which it was desired to detect enemy attackers in the time period of 1956 to 1960. This would be of the order of 100,000 ft against an air-to-surface missile threat. This radar would have to perform height-finding or be designed to be used with a height-finder.

If the all-altitude Muldar design proved satisfactory and the data transmission and handling problems could be solved, as well as the problem of assimilating all of these data at the few central control centers, Muldar might be the backbone of the future network, replacing the AN/CPS-6B and AN/FPS-3 radars (or the AN/FPS-7 radar) for high-altitude coverage in addition to providing low-altitude coverage. However, the all-altitude Muldar appears to be somewhat more difficult technically than the low-altitude Muldar, so that it would seem reasonable to start by solving this problem with a low-altitude set, integrating it with the existing high-altitude network. The decision as to whether or not to work toward a network composed entirely of all-altitude Muldar cannot really be made until it becomes evident that there is a high expectation of developing a satisfactory set. In addition, the possible requirement of defense against a ballistic-missile threat may affect this decision. In the present study both lines of possible radar development were considered.

OVEROCEAN COVERAGE

The picket-ship radars using the AN/SPS-6B were assumed to be deployed with a maximum spacing of 150 miles; it was felt that such spacing would give satisfactory blip/scan ratios throughout the picket-ship coverage, as in the case of ground radar. A 150-mile spacing would just extend the pattern of the ground network, retaining the same low-altitude limitations.

For the earlier years, when AEW coverage may be provided by the AD-3 (or a similar type of airplane) carrying an 8-ft AEW antenna, the predicted range was such that it was felt that the airplanes would have to be spaced about 125 miles apart in order to give solid coverage in the AEW belt. In later years, when PO-2W's become operational with 17-ft antennas, this spacing could be increased to about 200 miles and still result in satisfactory coverage. It might be made even larger if it were not for the problems of data relay, rain-cloud shadows, and atmospheric trapping. There was also the feeling that too much reliance should not be placed on a single airplane in view of the possibilities of breakdown, enemy action, and bad weather. The 200-mile spacing was therefore based on both calculation and judgment.

Because of the line-of-sight restrictions, picket ships spaced 150 miles apart can only achieve coverage down to about 5000 ft, as in the ground-radar case. In order to obtain overwater coverage at altitudes below 5000 ft, it would be necessary either to space the picket ships so that they would be much closer together or to deploy one or the other of the AEW radars mentioned. If it is desired to achieve coverage down to several hundred feet, it was determined in

this study that such coverage could be provided more cheaply by AEW radar than by closely spaced picket ships. Since a very-low-altitude seaward attack definitely appears to be one of the likely attacks against which we should be protected, a firm requirement exists for AEW coverage. This raises the question as to whether there is still a need for picket-ship coverage.

It was concluded that it would be advantageous to retain some picket ships for several reasons. First, if adjusted to give satisfactory low coverage, the AN/APS-20A radar, with its 8-ft antenna, and even the AN/APS-20B, are not quite satisfactory at high altitudes. This is the region where the picket-ship radar could best augment the coverage. Secondly, some of the data handling, threat evaluation, etc., might be done more effectively from the picket-ship control rooms. Much more equipment and many more people could be stationed there than in a single-engine AD-3, or even in a B-29 (without considerable modification), although the PO-2W should be more independent. Finally, the picket ships, by virtue of being out to sea, could serve as check points and clearance stations for defense identification procedures. This would increase the reliability in making correct identification of aircraft.

A question which is frequently brought up in connection with overwater coverage has to do with the vulnerability of these stations to enemy attack. It is believed that in the case of AEW there would be no acute danger, because the only type of aircraft expected to attack this far from its home base would be an unescorted bomber. In all probability, it would be difficult for an attacking bomber to shoot down an AEW airplane, since the AEW airplane, having very good surveillance data, could fall back when hostile bombers were detected. However, there is some thought that the picket ships might be vulnerable to submarine attack. For this reason, in costing the picket-ship network in the study, it was assumed that these would be DE(R)'s, which can take fairly effective antisubmarine precautions.

PRACTICAL PROBLEMS IN DETECTING ENEMY RAIDS

The preceding discussion has been concerned principally with the performance of the equipment in the radar network. It is also important to consider the performance of the network with its complement of operating personnel. Only by considering experience in World War II, or in large-scale exercises, is it possible to deduce the over-all network probability of detection.

As defined here, this means the probability that an enemy raid will be detected in such a way that there will be data in the air defense direction centers which will permit the processes of identification, evaluation, and assignment

of weapons to be initiated. Furthermore, these data must arrive in time to permit interception to be completed before the raid reaches the local-defense zone or bomb-release line, as the case may be.

In discussing this problem three quite different cases must be considered. The first is the so-called sneak attack, in which a few individual bombers, each carrying an A-bomb, attempt to penetrate our radar network unperceived in order to reach their desired aiming points. The second is a mass attack made by large, tight formations of bombers where perhaps only a few carry A-bombs and the others act as escorts. The third case is a combination of the other two, in which perhaps large numbers of single aircraft, or both single and formation-flying aircraft, attack. In the first case, the hope of the offense is to evade detection or prompt identification, whereas in the second and third cases, he brings in his additional bombers to saturate our control capacity and to divide the fire of our defense weapons.

Consider for the moment a single bomber in a sneak attack. The preceding curves and tables have shown that if we have only to contend with an average amount of maintenance degradation, the cumulative probability of detection by the first radar which the bomber approaches becomes very high by the time that the bomber is within about 100 miles of the radar set. This is true if the bomber is approaching at medium or high altitude against AN/CPS-6B or AN/FPS-3 radars, or if he is coming in at low altitude against the low-altitude gap-filler radars deployed around the large radar.

If this were all that there was to the problem, it would be satisfactory to call the probability of detection unity and proceed to the next question. However, in the larger framework of the whole radar network, the problem is more complex than this because, as a result of other traffic, lack of attention, or confusion as to what is going on, operators sometimes do not notice blips when they appear on the scope. This is again the question of the operator factor. The cumulative probability of detection on a high-altitude raid against the AN/CPS-6B radar, computed for the most probable maintenance degradation and considering various operator factors, was shown in Fig. 78. Extrapolating from these results, and considering nonradial approaches, it can be seen that if both the operator factor and the maintenance condition are poor, there is a certain finite chance that the bomber will not be detected at all by the radar. Even if the operator does see the blip, there is still a chance that the information will not get to the plotting board.

Two factors tend to offset the above degradations of individual radar performance. First, it is planned that by 1952 or 1953, radar coverage will exist

in a belt outside the boundaries of the ZI, so the number of aircraft *entering* the network will be very low. The chance of nondetection due to other traffic and confusion will therefore be lowered for these areas which are far from the high-traffic regions. Secondly, the radars will be connected into networks. Some British data, generally corresponding to the dense-traffic case, are given below for both single radars and networks.

Data from British Exercises

An estimate of the level of efficiency obtainable by individual radars was made possible by the experiences of the British in their two most recent exercises, Stardust and Emperor. Some data from these exercises are summarized in Table 31. Where more than one aircraft is indicated, the aircraft flew in a reasonably tight formation.

With the exception of the CHEL performance on low-level flights, the detection probabilities are consistently greater than 0.70. The set which provides most of the British early warning is the high-looking CHL. For the last three exercises, Foil (not recorded in Table 31), Stardust, and Emperor, the performance of CHL on B-29 and B-50 aircraft at about 25,000 ft has been fairly consistent, essentially all such aircraft being detected at ranges greater than 50 miles along their lines of approach. The above data refer to nonjamming conditions; no quantitative data are available on the detection of raids where electronic countermeasures (ECM) were used. Qualitatively, British experience has been that the ECM used to date tends to increase the range at which a jamming aircraft is detected. However, this effect is accompanied by an inability to track the aircraft closer than within 40 or 50 miles off the coast, or within a similar distance of a radar station.

A second factor tending to offset the degradations discussed is the combination of radars into a network. When an aircraft penetrates the area of surveillance of two radars, its probability of detection is greater than when it penetrates into the surveillance area of but one of them. Thus, it is to be expected that the over-all network performance will be better than that of the individual radars. The British experience with composite network performance in Exercises Stardust and Emperor (again for non-ECM conditions) is presented in Table 32.

With the exclusion of low-level flights, the over-all detection rate is well above 85 per cent. These numbers represent the average activity level during the sampling periods and do not necessarily indicate the efficiency with which other simultaneous raids were being handled.

Table 31

BRITISH EXERCISE RESULTS ON RAID DETECTION BY SINGLE RADARS

Exercise	Type of Radar	Number and Type of Aircraft in Raid	Altitude (ft)	Number of Raids* Examined	Number of Raids Detected	Probability of Detection	Probability of Detection, 90 Per Cent Confidence Interval
Stardust	CH	1 Lincoln	16,000 to 22,000	79	64	.81	.73 to .87
Stardust	CH	1 B-29/B-50	15,000 to 25,000	11	9	.88	.66 to .98
Emperor	CH	4 to 8 Vampires	26,000 to 35,000	60	48	.80	.75 to .82
Stardust	CHL	1 Lincoln	16,000 to 22,000	105	83	.79	.73 to .84
Stardust	CHL	1 B-29/B-50	15,000 to 25,000	28	20	.71	.57 to .82
Emperor	CHL	4 to 8 Vampires	26,000 to 35,000	47	33	.70	.64 to .76
Emperor	CHEL†	Low-flying raids; mostly pairs of Hornets at 200 ft	....	96	45	.47	.43 to .51
Emperor	CHEL‡	Low-flying raids; mostly pairs of Hornets at 200 ft	....	97	22	.23	.21 to .26

* Raids which entered the plotting area of a station at maximum range.
† CHEL stations sited between 500 and 800 ft above sea level.
‡ CHEL stations sited between 200 and 300 ft above sea level.

Table 32

BRITISH EXERCISE RESULTS ON RAID DETECTION BY NETWORKS

Exercise	Number and Type of Aircraft in Raid	Altitude (ft)	Number of Raids Examined	Number of Raids Detected	Probability of Detection	Probability of Detection, 90 Per Cent Confidence Interval
Stardust	1 Lincoln	16,000 to 22,000	72	62	.86	.79 to .93
Stardust	1 to 4 B-29/B-50	15,000 to 25,000	17	16	.94	.79 to 1.00
Emperor	1 to 3 B-29/B-50	20,000 to 35,000	17	17	1.00	.92 to 1.00
Emperor	2 to 8 Vampires	26,000 to 35,000	24	23	.96	.89 to 1.00
Emperor	1 to 3 Mosquitoes	10,000 to 17,000	13	11	.85	.72 to .93
Emperor	1 to 4 Mosquitoes	20,000 to 25,000	7	7	1.00	.80 to 1.00
Emperor	1 Spitfire or Mosquito	Below 500	8	3	.38	.23 to .56
Emperor	Hornets (Firebrands and Fireflies)	Below 200	153	58	.38	.35 to .41

Effect on Total Attrition

The over-all probability of detection by the radar network will be discussed in Part II of this report in connection with its action as a limiting asymptote, as defense-weapon budgets increase, on bomber attrition. If there is a finite chance that bombers will not be detected in time for kills before their bomb-release points, then a certain fraction of the bombers will get through, regardless of the number of defense weapons bought. Although it is impossible to estimate this effect with much confidence, it might be assumed, as a planning factor, that the fraction of bombers acted upon by the weapon system would be 0.9 prior to 1957 and unity thereafter, provided the radar networks were designed to give coverage at the attack altitude.

V. Traffic-Handling Capacity

An important requirement is that the traffic-handling capacity of the radar network be adequate to provide the defense with an air-surveillance picture. In this section traffic-handling capacity is defined as the number of independent tracks (including unknowns and friendlies) which can be satisfactorily processed at a radar or control center, the time delays, gross mistakes, and inaccuracies being held at an acceptable minimum. The processing primarily provides information for defense actions beginning with detection and ending when a specific track is turned over to a weapon director. In the present system

this includes the processes of detection, plotting on a situation board, establishing a track, supplying height, identity, and size data for the track, evaluating the threat of any hostile track, and making a decision as to what weapons should be assigned against each hostile track.

The adequacy of a station's traffic-handling capacity depends principally on three things: (1) the traffic load imposed by the air situation, (2) the number of operators and the quantity of equipment, and (3) the degree of help given to the operators by the design of equipments and procedures. To some extent, the adequacy during a raid also depends on the control philosophy —close control, loose control, or modified loose control—because the type of control determines the extent to which the enemy raids are broken down into separate tracks. Control philosophy is much more important in its effect on control capacity, however, and this will be discussed in Sec. VII.

NATURE AND EXTENT OF AIR TRAFFIC

In considering the nature and extent of the actual traffic imposed upon the network, two cases must be clearly distinguished: First, there is the normal peacetime case, such as we are experiencing at the present time, in which the traffic consists of civil airlines, private flying, and routine military flying. Practically all aircraft are moving as single aircraft. Secondly, there is the traffic during hostilities.

Prehostilities Traffic

The amount of peacetime traffic from overseas entering the borders of this country, or the borders of the Air Defense Indentification Zones surrounding this country, is not very great. Since the Canadian radar stations will extend the radar network some distance beyond the United States–Canadian border (at least in the East), it is permissible to define entering aircraft as those originating outside a 100-mile band stretching across the north side of the border. Then the Air Division suffering the largest influx of these aircraft is the 32nd, in the New England area, where the traffic approaches the United States over the Labrador–Newfoundland–North Atlantic routes. Examination shows that aircraft of all types entering here seldom exceed twenty-five per day and that probably no more than five appear simultaneously (i.e., within a given 30-minute period).

The traffic within the country, however, varies from very small amounts in the midwest and mountainous regions to heavy traffic in the Washington, New York, Boston, Pittsburgh, and Chicago areas. For example, the typical

peacetime traffic in the radar area containing New York City is 390 simultaneous aircraft at the daily peak (3 o'clock in the afternoon). This is the number of simultaneous tracks which the GCI station would have to carry.

The pattern of traffic described above is the background against which the first Soviet raid would probably have to be identified.[13]

Traffic during Hostilities

The heaviest traffic which we could expect to have to handle in the air defense system would occur if this normal traffic had superimposed on it a heavy saturation raid of the largest number of Soviet bombers that the USSR could send and, in addition, the largest number of interceptors we could manage to scramble into the air battle. After a few hours our own E-day traffic might add to the confusion. It is felt that a typical mass raid would see 200 to 400 Soviet bombers within the ZI and the same number or slightly more friendly interceptors. It is unlikely that the enemy aircraft would be distributed uniformly all over the country; even if they were, this would not be a very heavy traffic load.

To determine the areas where the densest air battle traffic might occur, a study was made using the target system of the present study and considering plausible bomber attacks and plausible interceptor deployment. To give an idea of maximum loads—not typical loads—four hundred bombers—more than most estimates predict—were assumed to reach the ZI. A count was then made of the expected numbers of bombers and interceptors in the primary area of responsibility of any one GCI.[14,15] Out of several typical raids of different strategies, the maximum number of bombers in one radar area (that of site P-62, near Youngstown, Ohio) was 152 and the number of interceptors was 137. (See Fig. 84, page 275.) Adding this traffic to the normal daily peak traffic of 196 simultaneous aircraft over this area gives a total of 485 tracks, which is also representative of such congested areas as New York or Chicago.

[15] These would be instantaneous peak loads, the assumption being that the bombers would fly in such patterns as to be over the GCI area approximately simultaneously.

It seems only reasonable that the Air Defense Command would do everything possible to divert or ground normal military and civilian traffic in the event of such a mass raid; therefore the probability that these two heavy burdens would occur simultaneously must be carefully considered before any such stringent requirements are placed on the traffic capacity of our network. At the present time no detailed study exists of the feasibility of diverting our friendly traffic and no complete operational-command structures are set up to do so in the event of an emergency. However, in calculating traffic capacity, etc., the present study has given consideration to the possibility that it will be generally feasible to separate these two kinds of traffic and to divert and ground the normal nonparticipant military and civilian traffic while a large air battle is in progress. This implies certain extensions to the presently planned radar network.

Another case to be distinguished is that in which a relatively small number of Soviet bombers, seeking to make a sneak penetration of our defenses, would be superimposed on our normal peacetime civil and military traffic load. In order to have an effective defense against this kind of attack, we must have a satisfactory close-control or modified close-control system, since the small number of bombers would require us to vector the fighters rather accurately to single targets. Hence, in this case, we have a requirement of effective close control in the presence of peacetime traffic only slightly increased by Soviet bombers and friendly interceptors.

Emergency Military Traffic

If hostilities have already begun or if unequivocal warning of hostilities has already been received, there may be heavily augmented military traffic which is not directly concerned with air defense but which will tend to saturate the network. For example, estimates of the traffic generated by the mobilization of the SAC strikes, with the attendant MATS traffic, indicate that as many as twelve or fifteen such tracks might occur at one time in the area of a single radar.

Summarizing,[16] it may be said that the most favorable situation for the defense forces will be one in which our radar system is so deployed that identification of unknown tracks can be performed in regions outside the boundaries of the ZI—off the two coasts and in Canada—and perhaps in some

[16] Table 33 on page 274 summarizes some of the most pertinent air-traffic estimates for comparison with various equipment design goals.

lightly traveled regions inside the ZI.[17] After identification of hostile aircraft is made, the diversion or grounding of civil air traffic and nonessential military traffic should be attempted. The traffic capacity needed to perform the initial detection, to establish tracks, and to identify hostiles will then be very low.

DESIGN OF EQUIPMENT FOR THE REQUIRED LOADS

At this point a review of various development programs in the field of ground-radar data handling is in order so that the preceding discussion of traffic-handling capacity can be summed up in terms of the requirements which these various developments must be able to meet.

As a starting point, consider the present radar system. The AN/CPS-6B control room, which forms the backbone of our network in high-traffic regions, provides four B-scope operators who perform the detection function and a possible fifth operator to supervise. These four people tell plots by telephone lines to plotters standing behind a vertical board. The plotters, assisted by overlap plotters with telephone lines to adjacent radars, mark the plots and the tracks on the board. It is estimated that the traffic capacity of this part of the system at present varies from 10 to 20 simultaneous tracks, depending on the training and skill of the personnel involved.

Identification information is furnished by the identification section, which works with flight-plan information. They observe the tracks on the vertical board and, after establishing identity, enter the information by track number on a "tote board."

There are height operators who observe tracks on the vertical board and furnish height data which are also entered on the tote board. Similarly, estimates of size are entered by a size estimator (who is sometimes one of the B-scan operators).

The senior director (formerly called the master controller) can see the vertical board, the tote board, and the status boards which show the readiness condition of the interceptors under his control, as well as weather information, etc. When he decides what action should be taken, he informs directors (formerly called duty controllers) to place particular bomber tracks under attack with given interceptor flights.

At the present time the performance of the new radars provides data that are directly available at the GCI room for an area about 200 to 300 miles

[17] A step in this direction is the present practice of assigning offshore areas of concentration for detection and the establishment of so-called "free areas" around major cities where identification is not attempted.

across. The primary area of responsibility of these stations, however, is usually considerably smaller, somewhat hexagonal in shape, and perhaps 170 miles across.

At the present time there is considerable activity both at the Rome Air Development Center (RADC) and in Project Lincoln [18] to develop devices which will improve the performance of this GCI control room and which can be ready for field use within the next year or two. These constitute the "quick-fix programs" of Project Lincoln and RADC.

The TPI

The most important item with which these programs are concerned is the target-position indicator (TPI). In this system, data from the radar plan-position indicator (PPI) are photographed and projected on a horizontal glass working surface. Plotters sit around this surface, marking the plots with chalk and doing the basic filtering and establishing of tracks. (This surface is the so-called "dirty" board.) By using different colors of chalk, they can cause only the desired track information to be photographed by a second camera, which projects this "clean" information upon a vertical plotting board in the GCI room. The RADC TPI shows only the latest radar scan as a *negative* picture, i.e., black dots on a light surface.

The Project Lincoln TPI proposes to show a number of radar scans simultaneously, so that track information will be immediately visible. By using a Land camera, this TPI will show the scans as a *positive* picture, the targets being bright against a dark background. Furthermore, it will use color in such a way that moving targets will be seen as a series of red and green dots; it is intended that fixed targets will appear as yellow areas. It seems clear that the addition of color and track information will be an advantage, so if the Project Lincoln TPI meets its development goals and does not have an excessive cost, it should be somewhat better than the RADC TPI. The Project Lincoln TPI might also be able to distinguish aircraft from random chaff droppings. The RADC TPI is, however, somewhat further along in development and will probably be slightly cheaper to operate.

In either event, the main advantage to be gained by use of the TPI is an increase in the number of tracks which can be handled. Preliminary tests indicate that two to four times as many tracks can be handled in this way as in

the present radar control rooms, using the same number of plotters. Conversely, savings in manpower can be made by eliminating some of the plotters, tellers, or scope operators of the present system. In addition to the TPI, both RADC and Project Lincoln have other items in their quick-fix programs. These probably would not make so much difference in traffic capacity as the TPI's. It now appears that the TPI's will be tested in 1952 and that they could be installed in the network in late 1952 or early 1953.

GRS and CDS

By about 1955 a somewhat more sophisticated system may be possible if the RADC project called the "Ground Reporting System" (GRS) is satisfactorily developed and produced.[19] At the present time it seems that this system may develop in one of two ways: (1) it may make considerable use of the techniques of the British Comprehensive Display System (CDS), merely modifying it for USAF use and adding the other features necessary for a complete rework of the GCI data-handling facilities; or (2) it may make use of the more nearly automatic track-while-scan channel developments in a program now called "semiautomatic tracking." In either event, this system is designed to permit 100 separate tracks to be handled in the area of responsibility of a GRS station. This may be the area of one GCI, or, in later years, it may be better to make this the area of several adjacent GCI's.

These systems, as presently proposed, operate quite differently from the present system in that there are separate scope consoles for the various functions of data handling and there is no large board showing plotted track data. Instead, some persons are assigned the job of detecting targets, and others are assigned the task of tracking given targets continuously. The changing track information is put into a central "store." By means of this store, the identification personnel, the height-finder, the size estimator, and so on, can draw out or insert the data on the track in which they are interested at the time. When they have found the identity, height, or size data, they can enter these data in the store with the track. The master controller or weapon assigner can then examine all the tracks in the store, or the tracks in various identity classes (such as only unassigned hostiles or only friendly interceptors), in order to make his decisions. Finally, the weapon directors have a display which shows them the track of the bomber for which they are responsible, the fighter which they

are controlling, and the height, size, and other data associated with the tracks.

It is hoped that a system of this type will greatly increase the traffic-handling capacity over that of the present system, minimize mistakes, and perhaps even reduce the number of personnel.

Digital Techniques

An entirely separate development from all of those previously discussed is that being pursued by Project Lincoln. In this development it is proposed that a large digital computer be used to perform automatically many or all the functions of data processing. At present this system is visualized as handling the data from one whole air division in a single central place, so that the number of tracks in the area is quite large. The present design objective is to handle about 1000 simultaneous tracks. It is also their objective to make the functions involved in this data handling as automatic as possible in order to minimize the number of personnel, errors, and delays. However, in the present study, it was felt that the difficulty of obtaining automatic solutions to the problems of detection, establishment of track, identification, and continuous tracking through possible clutter, as well as to those of proper decision in the evaluation and assignment function and adequate performance in the control and return-to-base phases, is so great that a completely automatic system is probably many years in the future.

It is possible that some modified form of this system might be available by 1957 or 1958. This program is as yet so new that it is difficult to estimate what may happen in the next few years toward modifying or compromising the automaticity and centralization features. It is possible that the GRS program may well move in the direction of greater centralization, and perhaps use some digital techniques. In any event, the design objectives of 100 tracks in a GRS area and 1000 tracks in an air division are really not very far apart.

Summary

Present GCI installations can handle approximately 15 tracks. Adding TPI should raise the level to approximately 30 to 40 tracks, and the addition of a GRS should raise this number to approximately 100 tracks. The use of a centralized digital system should raise the capacity per air division to 1000 tracks, which is roughly equivalent to 200 tracks per GCI area. In terms of these track-handling estimates, it is interesting to consider the estimates of air traffic summarized in Table 33. The areas mentioned in the table are shown in Fig. 84.

Table 33

ESTIMATED AIR TRAFFIC WITHIN CERTAIN AREAS

Area	Relative Amount of Traffic	Radar Sites Used	Number of Simultaneous Tracks Expected			
			Normal Peacetime Traffic in ZI, above 5000 ft	Total Normal Peacetime Traffic in ZI	Saturation Raid, Bombers Plus Fighters	Normal Peacetime Tracks Entering ZI
GCI primary area of responsibility	Heavy	P-62	17	196	289	0
	Typical	P-50	4	94	...	0
Possible Ground Reporting System area (3 GCI primary areas of responsibility)	Heavy	P-63 P-30 P-55	104	565	131	0
	Typical	P-50 P-10 P-45	22	267	246	4
Air Division	Heavy	(26th)	331	1411	320	5
	Typical	(32nd)	49	406	140	5

NOTES:

1. The areas examined were restricted to those within the Eastern Air Defense Force area, where traffic capacity is most important.
2. All the peacetime figures refer to the peak hour of an average July day, July being the peak month. *Heavy* and *typical* figures are differentiated only by the area examined, 50 to 99 tracks constituting a typical-traffic area and more than 100, a heavy-traffic area.
3. Estimates of tracks entering the ZI include only military and commercial aircraft penetrating from outside the basic Canadian–United States radar network.
4. Execution of SAC and MATS deployment plans might add as many as 15 tracks in some GCI primary areas.
5. The traffic in the combined areas of P-30, P-55, and P-63 is unusually heavy and is estimated to have more than the usual proportion of high-altitude military traffic.

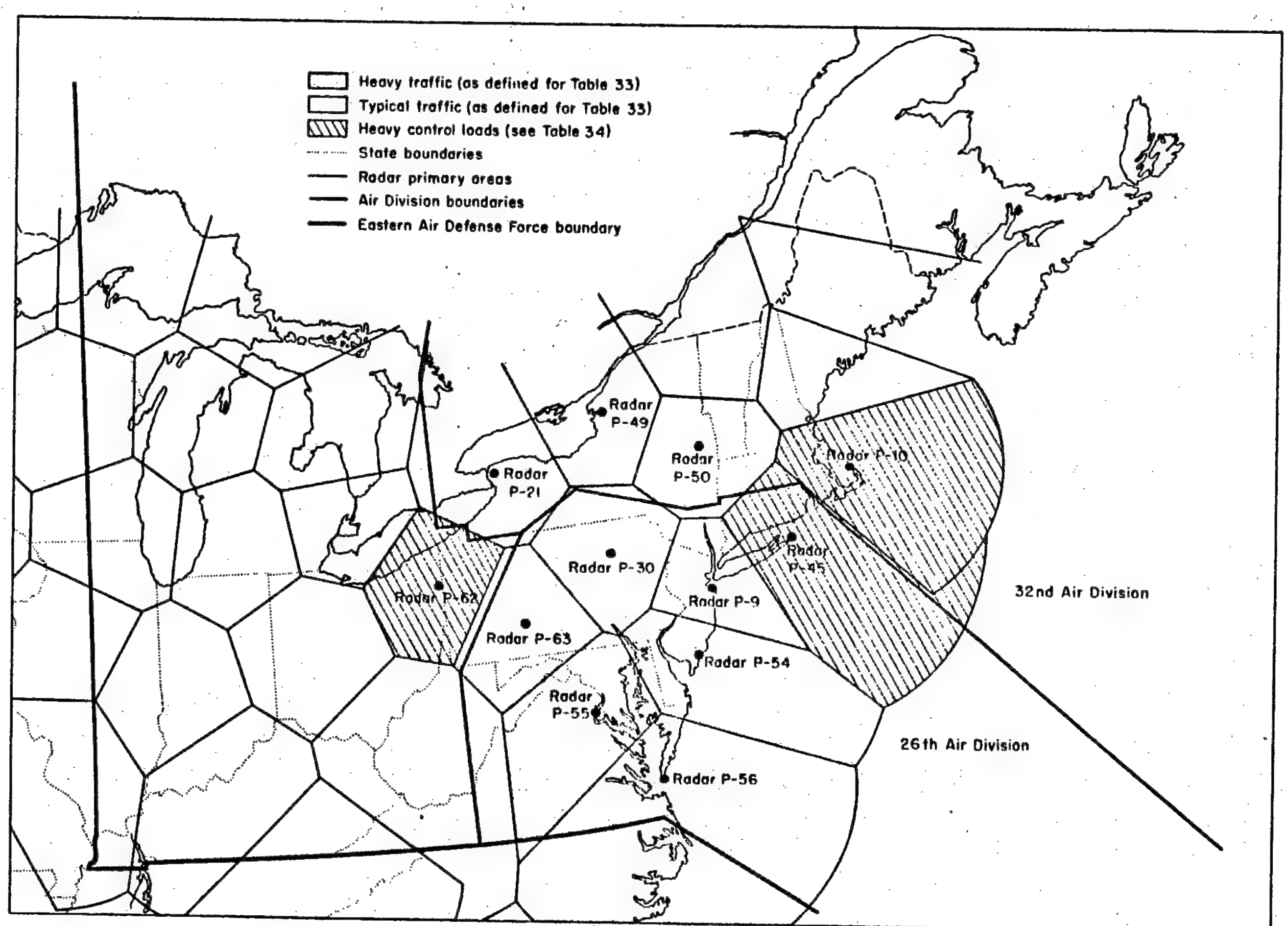


Fig. 84—Areas having high traffic density or heavy control loads

VI. Identification

Closely related to the problem of traffic handling is that of identification, since hostile aircraft must be sorted out from the background of air traffic. If this background traffic is heavy, the difficulty of the sorting process is increased.

At the present time, identification is largely done by matching radar data with flight plans, which are filed in advance by pilots who intend to fly through Air Defense Identification Zones (ADIZ's). A first attempt at identification is made at the ADDC or GCI station by a one- or two-man detail. Teletype flight-plan messages are compared with the main plotting board, and plots which are within both 20 miles and 5 minutes of the projected flight plan are called friendly. If identification cannot be made promptly at the radar, the job is turned over to the Air Defense Control Center (ADCC). In an alternative method, now being tried in some areas, identification is done at an Air Movements Identification Section (AMIS), operated by the Civil Aeronautics Administration.

If the plot fails to coincide with a flight plan, interceptors (if available) are scrambled to make an investigation. The interceptor pilot is given a set of "rules of engagement," which is intended to be used as a guide in determining whether or not to fire on the intruder. These rules are independent of the preceding identification procedures that may have been carried out. Under the present rules of engagement an aircraft can be fired on only if:

1. It is manifestly hostile in intent.
2. It commits an overt hostile act.
3. It carries USSR markings and appears without prior arrangements.

Some of the inadequacies of the present system, as described above, were noted in Chap. 2 (page 14). Also given in Chap. 2 was a series of steps that might lead to an increased identification capability. These steps may be summarized as follows:

First, the coverage of the radar network should be extended well outside the region of most likely targets of Soviet attack. The most difficult part of such coverage would be the provision of picket ships or AEW aircraft for overocean coverage. It is also important to extend the coverage down to the lowest probable bomber flight altitude in a given terrain. (At present, largely because of the lack of low-altitude coverage, almost no attempt is made to identify tracks that are less than 4000 ft over terrain.)

Secondly, the basic identification operation should take place in a belt outside the high-traffic areas of the ZI. Insofar as possible, this plan should be complemented by a plan for the rigorous control of internal traffic, including the authority and ability to ground friendly aircraft on short notice or to divert them from critical areas.

Thirdly, a series of procedures must be required of friendly aircraft. These procedures should be designed to minimize the probability of identifying friendlies as hostiles, as well as the converse; they should also be designed to lessen the reluctance of the interceptor pilot to fire on an aircraft that might be friendly. A suggested series of procedures was outlined in Chap. 2 (page 15). Actually, the selection of a workable set of procedures depends on detailed knowledge of such things as civil air-traffic control and airline operation, so that it will probably be necessary to set up a working group representing these various fields before detailed plans can be made.

Finally, it should be pointed out that, once having arrived at the most reasonable identification policy, the USAF must convince the public of the merits of this policy. The informed co-operation of both commercial and private airplane operators will be needed in view of the probable inconveniences that they may be asked to undergo. Furthermore, even the best practicable plan will probably involve a small, but finite, chance of shooting down a friendly airplane. If so, the public should be educated in advance regarding the comparative danger of erroneous attacks on friendly aircraft and the bomb damage that might attend a lax identification policy.

VII. Control Capacity

The discussion of traffic-handling capacity in Sec. V dealt with the ability of the network to maintain a picture of the air situation, primarily for the defense actions preceding the assignment of weapons. This section treats the problem of controlling area-defense weapons from take-off to the point where their airborne radars (or their pilots' visual faculties) can detect the enemy. The same system usually helps manned aircraft return to base. The discussion is in terms of manned interceptors. Comments about the special control requirements of area-defense missiles appear in Chap. 8.

At the present time, interceptors are controlled by "directors" (formerly called "duty controllers") at the ADDC's and GCI's. The standard arrangement consists of a group of three consoles: a height-range scope (with an operator) in the center and PPI's, manned by directors, on either side. Having

been assigned a hostile track by its track number, the director locates the hostile aircraft on his own PPI. As soon as radio contact can be made with the interceptor assigned to him, he begins to vector the interceptor, by voice, into a position which is favorable for AI or visual contact with the hostile airplane. This process requires some degree of skill if the airplane speeds are high. There is no gadget, comparable with the Craig Computer of World War II, which is in general use today to aid the director. (Present-day speeds are deterrents to the use of the Craig Computer.)

Skilled directors can conduct two simultaneous interceptions if they are properly staggered. The AN/FPS-3's have three PPI's (expansible to ten) for directors and the AN/CPS-6B's have eight, which places a definite limit on station control capacity. In addition to this, the ability of the senior director to assign tracks becomes strained at about this same point, and in some cases there may be a bottleneck in air-to-ground command channels. These station capacities, as pointed out in the following discussion, are inadequate in certain localities. Some possible ways of increasing control capacity are therefore considered below.

REQUIREMENTS FOR CONTROL CAPACITY

Various parts of RAND's Air Defense Study were drawn on in estimating the requirements for control capacity. These studies permitted estimates to be made of the number and types of interceptors available to the Air Defense Command in a given year, the number of bombers available to the USSR, the Russian stockpile of atomic bombs, the number of airplanes and bombs the Russians would commit to one raid, the most probable types of bomber formations, and the targets which might be attacked. The portions of the study reported in Part II of this report helped in estimating the defense level represented by a given interceptor force, the deployment of interceptors over the United States, and the optimum number of targets to be attacked under a given set of conditions. All of these factors influence the number of duels that might take place in a given locality.

A detailed study was made of the *maximum* loads to be expected in the period around 1954.[20] By using this study as a basis, extrapolations can be made to later years or to less severe conditions. The key estimates and assumptions, all pointed toward finding maximum loads, were:

1. That 400 Soviet bombers would attack, using strategies which would concentrate the attack.
2. That a plan to attack about 150 population targets or 50 to 200 industrial targets would yield to the enemy the greatest damage to our targets.
3. That radars would be laid out according to present plans.
4. That the interceptor defense of the ZI would consist of 61 squadrons.[21]

Several possible enemy strategies were investigated, both against population and against industry. The industrial strategies included mixtures of target types as well as concentration on single industries, such as steel or petroleum. Radar areas of primary responsibility, which included for each radar all the area nearer to it than to any other radar, were plotted on maps of the target system. These areas of primary responsibility were the regions examined for high control loads in each case.

The number of air duels was assumed to be equal to the number of fighters or to the number of bombers, whichever was smaller. The results for some of the radars with the highest loads are given in Table 34. (For the location of these radars, see Fig. 84, page 275.) If it is assumed that the bombers will fly in close formation, or that the interceptors will attack in elements of two or three, the appropriate number of duels is not that shown in the table but can be found from the numbers of fighters and bombers engaged. Similar modifications are in order if it is assumed that close control will not be used under these conditions. If it is assumed that radars with overlapping coverage can give assistance to the heavily loaded station, the number of duels can be reduced. Table 34 also gives estimates for probable amounts of assistance, taking into consideration the loads already existing at the assisting stations.

If the radar network is to handle control loads such as those just estimated, both equipment and procedures must be altered, at least in certain localities. One possible step would be to increase the number of PPI's and directors at the radars. Not much is known of the extent to which this could be done, although British experience indicates that the senior director would be a limiting factor. A similar procedure, applicable in times when the kill-per-sortie rate is fairly low, is to vector several interceptors in formation against a single bomber. In the Pacific Northwest the 25th Air Division has been trying a procedure in which a "fighter monitor" relieves the directors of the task of guiding interceptors to and from the combat zone.

[21] This assumption applies to the data given below

Table 34

MAXIMUM NUMBERS OF DUELS OVER VARIOUS RADARS

Location of Radar	Radar No.	Targets	Bombers over Radar Primary Area	Interceptors over Radar Primary Area	Duels under Control of Radar, Unassisted	Duels under Control of Radar, Assisted by Adjacent Radars
Montauk Point, N. Y.	P-45	Jet engines Atom bombs Aviation fuel Copper refining Alumina Explosives Propellers Washington, D. C.	68	108	68	45
Montauk Point, N. Y.	P-45	Atom bombs Electron tubes	72	133	72	45
Montauk Point, N. Y.	P-45	Population	65	77	65	50
Cape Cod, Mass.	P-10	Bearings Aircraft engines Propellers	84	87	84	60

Location of Radar	Radar No.	Targets	Bombers over Radar Primary Area	Interceptors over Radar Primary Area	Duels under Control of Radar, Unassisted	Duels under Control of Radar, Assisted by Adjacent Radars
Youngstown, Ohio	P-62	Steel	152	137	137	59
Youngstown, Ohio	P-62	Steel SAC Atom bombs Copper Alumina Jet engines Propellers Aviation fuel Bearings Population Washington, D. C.	66	90	66	32
Zwolle, La.*	Mobile GCI assumed here	Oil	112	50	50	26

* 60 miles south of Shreveport, La.

Another kind of relief could come from the use of loose-control (or modified loose-control) techniques, in which the radar would broadcast to the interceptors the bomber coordinates, leaving the interceptors to determine their own positions and to compute vectors. As bomber densities increase, this technique becomes more and more attractive. The MX-1179 control system for future interceptors will provide certain features along this line, probably without much penalty in weight. There is also a possibility that future ground-control systems now being developed can be made to have adequate close-control capacities. These will be discussed next.

PLANS FOR MECHANIZING CONTROL

There are two principal lines of effort in the USAF toward the mechanization of interceptor control. These programs, which are being carried out at Rome Air Development Center (RADC) and at Project Lincoln, tie in with the programs discussed above in Sec. V. In the early phases of the work on control mechanization, it seemed that the major task was to find a solution to the changing trigonometric problem from which the vector was derived. As work progressed it began to appear that the trigonometric part of the problem was relatively easy. The most difficult problem now seems to be that of maintaining continuity in associating the trigonometric-computer inputs with data from a scanning radar. This must be done for many computers and a profusion of radar signals if high control capacity is to be achieved.

Track-while-scan devices, which have been under development since the end of World War II, are intended to accomplish the job described above. Unfortunately, the fully automatic versions of track-while-scan which have been developed are very complex mechanically and electrically and consequently expensive and not very reliable. Under the RADC "Ground Reporting System" (GRS) project, the present trend is toward the use of human operators. In one system they would monitor the operation of an aided tracking device; in another, they would follow the signal on a PPI with a marker controlled by a joy stick. (The latter is being adapted from the British Comprehensive Display System. The Bomarc missile-guidance unit will probably use a similar tracking device.)

The next step in the GRS is to associate (by switching) the track-while-scan outputs of a bomber and those of an interceptor with a trigonometric computer, called the Command Course Director. The resulting vector command is fed into a data transmitter, encoded, and sent by UHF radio to the interceptor. Although the ultimate limitations have not been fully explored, plans now

call for the handling of 40 duels at one site.

In the Project Lincoln system it is planned to do both the track-while-scan job and the vector computation with large-scale digital computers. The digital technique has certain advantages in avoiding confusion when large numbers of duels are handled at one place, but adequate computer storage may be hard to obtain. Research on digital-computer control, using the Whirlwind computer, is now being done at the Massachusetts Institute of Technology. Current plans, as yet indefinite, call for 100 to 500 duels to be handled at one site by means of this system, the one site probably being required to service the area of one air division.

VIII. Extent of Radar Coverage

At the time that RAND's study was being made, the official plan for ground-radar coverage, approved by the Joint Chiefs of Staff, called for 75 large radar stations in the ZI and 10 in Alaska. Eleven ADCC's were projected, only one of which was to be located at the same site (McChord AFB) as a radar. This program, after about 5 years of work on the equipment contracts, and 3 years of work on the associated and very difficult logistic problems, is nearing completion. Most of the sites are scheduled to become operational during 1952. In addition to the JCS-approved program, the Air Force has proposed a series of additional extensions of the coverage. Besides certain proposed agreements with Canada for northern coverage, there was a proposal first for 16 and then for 44 large mobile GCI radars of the AN/MPS-7 type. Most of the original 16 were intended for the protection of SAC bases. It has been the intention on all of these mobile radars that a number of them would be deployed overseas, particularly with TAC units, and that the exact deployment plans would remain flexible, taking into account the prevailing world military situation.

AUGMENTATIONS HYPOTHESIZED FOR STUDY

In RAND's study a particular deployment of ground radars, as nearly like that of the Air Force proposal of January, 1951, as available information would suggest, was taken as a minimum. It is called the "AF Plan" in the following discussion and consists of 75 AN/CPS-6B's or AN/FPS-3's and 16 AN/MPS-7's in the ZI, plus 29 similar stations in Canada. This plan, or, more precisely, the area covered by these radars, was taken as a base onto which extensions of ground and sea coverage were hypothesized. Most of the various proposals

made in recent months can be approximated by interpolating between RAND's hypothetical extensions.

For land coverage, four of these hypothetical increments were added to the AF Plan; these were called, in order, the Green, Purple, Brown, and Blue Plans. Their geographical distribution is shown in Table 35. These geographical categories were used in estimating costs, as described on pages 295 through 298. Likewise, a series of increasing overocean coverages was hypothesized; these coverages were called the Able, Baker, Charlie, and Dog Plans. In terms of picket ships spaced 150 miles apart, these plans called for 12, 23, 37, and 50 ships on station, respectively. (Figure 85 shows the AF Plan and its first three land and sea augmentations.) Actually, neither the overland plans nor the overwater plans were intended to imply given numbers of stations but rather given areas of coverage. For example, there would be more Muldar stations than conventional GCI stations in a given plan.

These various plans enabled RAND to make fairly realistic studies of (1) the effectiveness of coverages of various extents and (2) the cost of such coverages. This section discusses the layout of the plans and how their effectiveness was measured. The next section discusses their cost.

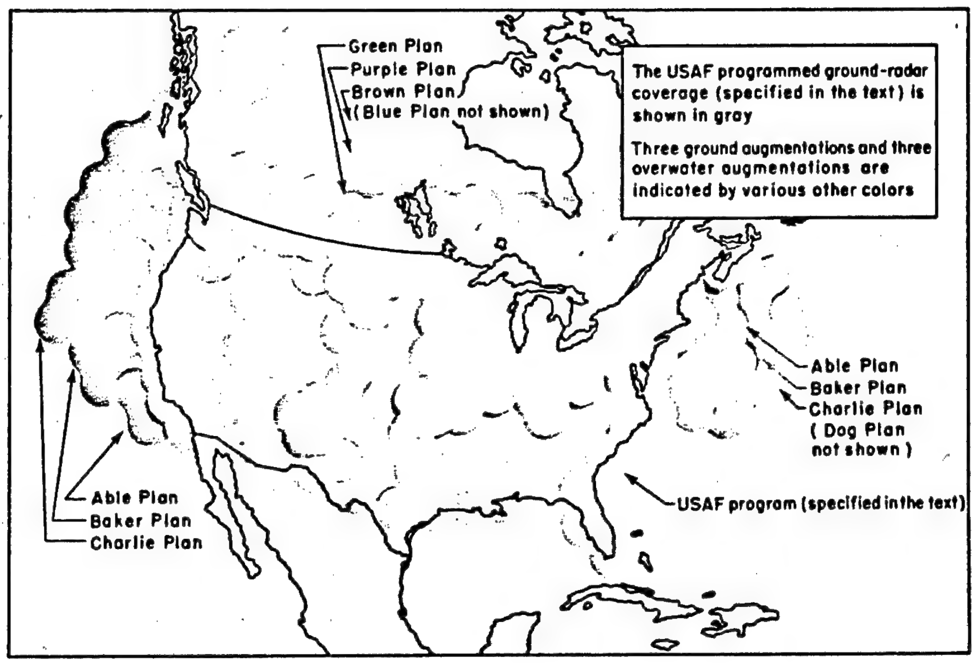


Fig. 85—Possible extensions of the radar network

Table 35

GEOGRAPHICAL DISTRIBUTION OF RADARS FOR RAND'S HYPOTHETICAL PLANS FOR GROUND-RADAR-NETWORK EXTENSIONS

Type of Station	Number of Stations per Geographical Zone*							
	Zone of the Interior	Lower Canada (Populated Portions)	Mid-Canada, with Rail Transportation	Mid-Canada, with Highway Transportation	Mid-Canadian Coast, with All-Year Ports	Mid-Canadian Coast, with Ports Open 3 Months Each Year	Mid-Canada, Reached Principally by Air	Arctic, Reached Principally by Air
Air Force Plan								
ADCC	11	3	0	0	0	0	0	0
ADDC	25	5	0	0	4	0	0	0
Other GCI	50†	11	0	0	9	0	0	0
Early Warning	..	..	0	0	13	0	0	0
Additional Stations for Green Plan								
ADCC	0	0	1	0	0	0	0	0
ADDC	4	0	3	0	0	0	2	0
Other GCI	7	0	5	0	1	0	5	0
Early Warning	..	..	8	0	1	0	7	0

* Types of stations and geographical zones are further discussed and defined in Sec. IX.
† Plus 16 mobile GCI's (AN/MPS-7).

Table 35—continued

Type of Station	Number of Stations per Geographical Zone*							
	Zone of the Interior	Lower Canada (Populated Portions)	Mid-Canada, with Rail Transportation	Mid-Canada, with Highway Transportation	Mid-Canadian Coast, with All-Year Ports	Mid-Canadian Coast, with Ports Open 3 Months Each Year	Mid-Canada, Reached Principally by Air	Arctic, Reached Principally by Air
Additional Stations for Purple Plan								
ADCC	0	0	1	0	0	0	0	0
ADDC	4	0	2	0	1	0	2	0
Other GCI	7	0	4	1	1	1	4	0
Early Warning	. .	. .	6	1	2	1	6	0
Additional Stations for Brown Plan								
ADCC	0	0	1	0	0	0	0	0
ADDC	4	0	1	1	0	1	2	0
Other GCI	7	0	3	1	0	2	5	0
Early Warning	. .	. .	4	2	0	3	7	0
Additional Stations for Blue Plan								
ADCC	0	0	0	0	0	0	1	0
ADDC	0	0	0	1	0	3	2	3
Other GCI	0	0	1	1	0	6	5	6
Early Warning	. .	. .	1	2	0	9	7	9

"COVER": A MEASURE OF THE EFFECTIVENESS OF EXTENSIONS

The effectiveness of a given plan of coverage was measured by the following series of steps. (Most of the measurements were made on radar networks with sites spaced about 150 miles apart, the effects of other spacings being inferred.)

1. The radars were plotted on a map, together with their coverage for a nominal radar range of 100 miles. On the same map, the United States target system (the "basic" list) of Chap. 4 was plotted. About 40 per cent of the Green, Purple, and Brown Plan radars were used to fill coverage holes in the ZI, and the remainder were used to extend the coverage outward.
2. The distance which the attacking bombers must fly through radar coverage to each target by the shortest logical path was found. Holes in the coverage did not result in subtractions of distance, but they were systematically plugged as the number of radars increased.
3. Before final distance measurements were made, the radar sites were adjusted to give coverages of at least 400 nautical miles to as many targets as possible. For the more extensive plans, in which all but 5 per cent of the targets had 400-nautical-mile coverage or more, the sites were adjusted to give the greatest coverage to all but this 5 per cent.
4. After the final distance measurements were made, each plan was characterized by a single number called the "cover." This quantity is the distance through coverage equaled or exceeded for all but 5 per cent of the targets, measured as stated above. Cover numbers for other percentages remaining were also used in some instances.
5. The cover numbers for a plan were then modified before they were used if the actual situation involved radar ranges appreciably greater than the nominal range of 100 nautical miles used in the map measurements. The use of the cover number will be discussed below; at this point it is sufficient to say that it was a useful way of characterizing the effectiveness of a complex combination of targets and radars.

This general procedure had several by-products. One was that a fairly realistic deployment of radars was obtained by the adjustment procedure of Step (3), optimized by the criteria stated therein. The ground-radar sites were

selected with due regard for the usual intuitive judgments concerning such factors as relative accessibility and location near populated places and military outposts. Even so, for each 25 sites spotted on the map, an allowance of about 2 extra sites was made in the costing to account for unforeseen difficulties.

Another by-product was that it became possible to match a given ground plan with a suitably complementary ocean plan. This can be done roughly by looking at the covers only, and more closely, as discussed below, if covers and costs are both considered. In all the tables and graphs given below, the non-compatible combinations (such as a Brown Plan combined with an Able Plan) will be omitted.

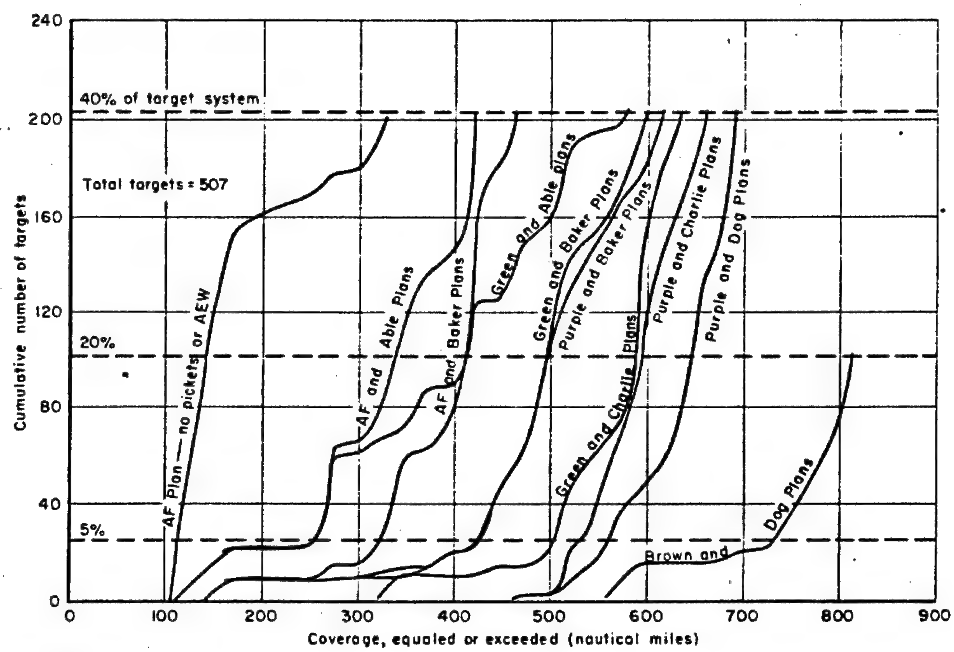


Fig. 86—Cumulative frequency distribution of radar coverage for various plans

The results of the coverage measurements for the compatible combinations are shown in Fig. 86, for which the basic target list, containing 507 United States targets,[22] was used. The all-but-5-per-cent covers for the various plan combinations can be found by reading off the abscissas at the 5 per cent dashed line; the all-but-20-per-cent and all-but-40-per-cent covers can be found in a similar manner.

[22] The list was revised to contain 501 targets after this part of the study was completed.

Finally, it might be pointed out that the cumulative frequency curves of Fig. 86 are more precise statements of a quantity analogous to the "radar-belt-depth" measure sometimes used in simpler models, where a heartland, or defended area, is used instead of the actual distributed targets. These curves permit statistical study of *distributions* of times available for defense actions. This is important in considering the defense of a target system so widespread and irregular as that of the United States. Similarly, where a single number must be used to characterize an extent of coverage, the cover is a more meaningful quantity than the belt depth.

NONCONTIGUOUS COVERAGE

There is a possibility of gaining some of the advantages of added network extent without paying the full price of *solid* coverage from the ZI outward. Some of the proposals which have been made are as follows:

1. The *Outpost Alerting System,* investigated at Watson Laboratories several years ago, involved a belt of simple radars across the North American Arctic. Some consideration was given to c-w operation and fixed beams.
2. A *line of AEW aircraft* patrolling between Newfoundland and Bermuda, or elsewhere off the Atlantic coast, was studied by the Operations Evaluation Group and, in a different form, was recommended by Project Charles.
3. The *Alaskan network,* and possible extensions thereof, has been suggested as a source of coverage for the defenses of the ZI, in addition to its role in the defense of Alaska.

All of these plans have the advantage of providing very early warning of approaching raids for a minimum cost. On the other hand, in some cases they are vulnerable to repeated "false-alarm" penetrations, and in all cases the enemy could fly a deceptive course in the free space between coverages. It seems clear that some gaps in our coverage can be tolerated in places where radar is very expensive, particularly if there is *some* chance of coverage in the gap (and provided the enemy knows it). The value of the added coverage must be measured in terms of the value of the additional defense-weapon activity that it permits. During the course of the present study, however, no satisfactory way was found to evaluate or design noncontiguous belts of radar, and no firm conclusions were reached on this subject.

IX. Cost of Radar Coverage

It is possible to estimate the costs of some types of radar installations—those which are a part of current programs—with a considerable degree of confidence. Costs of other possible programs, such as the Encoding Low-Altitude System[23] or B-29 AEW, can be estimated with somewhat less confidence, using present programs as a point of departure. Plans for some types of radar are not nearly far enough along for reliable estimates to be made, and uncertainties not only enter into the predictions of manufacturing costs, but also into operating procedures (and therefore personnel requirements) and into the required station spacing. These uncertainties apply particularly to Muldar and to PO-2W AEW airplanes equipped with 17-ft dishes.[24]

GEOGRAPHICAL VARIATIONS IN COST

In considering the conventional high-altitude network of AN/FPS-3's and AN/CPS-6B's, together with their associated control centers, an attempt was made to make separate estimates for each of eight geographical zones. Since transportation costs and labor costs were felt to be important variables, these factors were reflected in the choice of categories. The following were the categories used:

1. Zone of the Interior (the continental United States).
2. Lower Canada (the populated portions).
3. Mid-Canada, with rail transportation.
4. Mid-Canada, with highway transportation.
5. Mid-Canadian coast, with all-year ports.
6. Mid-Canadian coast, with ports open for 3 months each year (reached by air the remaining 9 months).
7. Mid-Canada, reached principally by air.
8. Arctic, reached principally by air.

In addition to the estimates for the high-altitude conventional-network units mentioned above, cost estimates for each zone were made for small radars of the AN/TPS-1D class, employing conventional military manning. This was the only one of the low-altitude radars for which the geographical cost variation was taken into account. It was possible to observe a trend from this

[23] This name is used to identify the supplementary low-altitude system described in Chap. 12.

case, and it seemed like a needless refinement to include the geographical factor in costing either Muldar or the Encoding Low-Altitude System, when their costs in the ZI are so uncertain and when the likelihood of their being installed in their planned form in the Far North is so remote. In effect, the ZI cost was used throughout for these two systems.

If thc conventional high-altitude network is ever extended beyond Lower Canada, it will undoubtedly employ a modified type of radar station, probably with lower traffic-handling capacity and fewer people. In RAND's study it was assumed that such a station would cost about the same as an AN/CPS-5 equipped with an AN/TPS-10B height-finder, and that it would require about the same number of people. All the costs given in this chapter for conventional high-altitude networks assume that these cheaper stations would be used for all Mid-Canada and Arctic zones instead of the AN/CPS-6B's or AN/FPS-3's.

Alaska, as a geographical zone, was not included, since even the most extensive plans did not reach Alaska. The planned Alaskan network was never considered as an extension of the main network but only as an influence on Soviet flight plans and in its role in the defense of Alaska itself. Newfoundland and its dependency, Labrador, are now a part of Canada, and no separate zone was set up in their case.

TYPES OF STATIONS IN GROUND NETWORKS

Costs per station were estimated for each of a number of types of stations. Various plans were considered to be composed of appropriate combinations of these types. Where specific equipment nomenclature is mentioned, this should be regarded as indicating a *cost class* rather than an exact model. As time goes on there will probably be a succession of equipments actually in service.

The types of ground stations for which cost estimates were made and the number of personnel at each station are given in Table 36. All have search radars and, if necessary, height-finders, except the Group Headquarters (of an Aircraft Control and Warning Group) and the Air Defense Control Center. For convenience, the name given was rather arbitrarily associated with each station type for the cost study, although there is some general usage of these names for other station types. In particular, note that AN/CPS-6B's are all called Air Defense Direction Centers and that AN/FPS-3's and AN/MPS-7's are called GCI stations. There is some current usage of "gap filler" to mean the mobile AN/MPS-7, but here that terminology is used only to mean a small station of the AN/TPS-1D class. "Early-warning" was used for the light-traffic stations assumed for use in Mid-Canada and the Arctic.

Table 36

PERSONNEL REQUIREMENTS OF GROUND-RADAR STATIONS

Type Name	Symbol	Typical Equipments	Estimated Number of Personnel
Group Headquarters	....	....	79
Air Defense Control Center	ADCC	....	255
Air Defense Direction Center	ADDC	AN/CPS-6B	233
Ground-controlled intercept station	GCI	AN/FPS-3 with AN/FPS-6 and AN/TPS-10B*	195
Gap-filler station	GF	AN/TPS-1D	47
Early-warning station	EW	AN/CPS-5 with AN/TPS-10B	120
Mobile GCI station	....	AN/MPS-7 with AN/MPS-6	188
Encoding Low-Altitude station	....	AN/CPN-4 search section	5
Muldar station	....	....	2
Muldar control center	....	Digital computer	200

* These height-finders were used in the costing. Present plans call for a number of AN/FPS-4 and AN/FPS-5 height-finders in addition to, or in place of, the AN/FPS-6's. These two types should cost about the same as the AN/TPS-10B's.

COSTS OF STATIONS IN GROUND NETWORKS

Estimated costs of ground stations of various types are given in Table 37 for sites in the ZI. A summary of initial and annual cost estimates for the various geographical zones is given in Table 38.

The breakdown used in Table 37 is explained in detail elsewhere,[25] but a brief amplification of the terms used will be given here. *Installations* includes such items as buildings, roads, and utilities. *Organizational equipment* includes vehicles, medical equipment, base-maintenance equipment, kitchen equipment, etc. *Initial stock level* includes both spare parts for the radars and stock levels of nontechnical items. *Indirect services* includes logistical support received from other military installations, such as supply, finance, and salvage services. *Intermediate commands* reflects a proportionate share, based on the number of personnel, of all costs of the Air Defense Command above the wing level. *Overhead* is a proportionate share of all Air Force costs other than those of the tactical operating commands; this includes a share of the cost of operating HqUSAF, Air Materiel Command, Air Proving Ground Command, etc. For many purposes it would be desirable to omit these last two costs (intermediate commands and overhead) because they are seldom known and are seldom

Table 37

ESTIMATED COSTS OF GROUND STATIONS IN THE ZONE OF THE INTERIOR

(Millions of dollars)

Item Costed	Group Hq	ADCC	ADDC	GCI	GF	EW	Mobile GCI	Muldar
Initial Costs								
Installations	.480	1.360	1.330	1.240	.120	1.070	.940	.025
Radar and ancillary equipment	.150	.150	1.617	1.698	.041	.558	1.467	.100
Telephone	.....	.....	.....	.....	.....	.....	.....	.030
Organizational equipment	.108	.348	.318	.266	.064	.164	.257	.006
Initial stock level	.096	.131	.713	.727	.030	.259	.629	.042
Transportation	.019	.061	.068	.057	.011	.035	.057	.002
Personnel								
Training	.279	.900	.822	.688	.166	.424	.664	.007
Travel	.016	.035	.033	.027	.007	.017	.026	.001
TOTAL INITIAL COST	1.148	2.985	4.901	4.703	.439	2.525	4.040	.215
Annual Costs								
Organizational equipment	.007	.022	.020	.017	.004	.010	.016	.001
Personnel								
Training	.071	.226	.205	.173	.042	.106	.166	.004
Pay and allowances	.277	.671	.668	.535	.129	.335	.517	.006
Travel	.016	.035	.033	.027	.007	.017	.026	.001
Operation and maintenance								
Installations	.030	.090	.080	.060	.020	.040	.040	.002
Telephone	....	.....	.100	.100	....	.....	.....	.015
Spares	.010	.010	.113	.119	.003	.039	.103	.007
Petroleum products	.008	.025	.023	.019	.005	.012	.018	....
Miscellaneous	.010	.071	.075	.055	.020	.041	.055	.001
Transportation	.064	.207	.189	.158	.038	.097	.153	.002
Indirect services	.049	.135	.151	.126	.027	.070	.109	.004
Intermediate commands	.107	.345	.315	.264	.064	.162	.255	.003
Overhead	.181	.497	.552	.463	.098	.256	.401	.014
TOTAL ANNUAL COST	.830	2.334	2.524	2.116	.457	1.185	1.859	.060

NOTE: The Encoding Low-Altitude System was estimated to have a total initial cost of $0.32 million and a total annual cost of $0.093 million. Muldar control centers were estimated to cost $4 million initially and $2.5 million annually.

Table 38

ESTIMATED COSTS OF GROUND STATIONS IN VARIOUS GEOGRAPHICAL ZONES
(Millions of dollars)

Geographical Zone	Group Hq	ADCC	ADDC	GCI	GF	EW	Mobile GCI
Zone of the Interior							
Initial cost	1.148	2.985	4.901	4.703	.439	2.525	4.040
Annual cost	.830	2.334	2.524	2.116	.457	1.185	1.859
Lower Canada (populated portions)							
Initial cost	1.250	3.263	5.287	4.755	.462	3.314	.....
Annual cost	.872	2.472	2.660	2.199	.480	1.262	.....
Mid-Canada, rail transportation							
Initial cost	1.414	3.753	6.265	5.689	.618	3.359	.....
Annual cost	.927	2.682	2.818	2.327	.551	1.403	.....
Mid-Canada, road transportation							
Initial cost	1.695	4.548	7.032	6.391	.704	3.944	.....
Annual cost	1.052	3.066	3.160	2.611	.623	1.582	.....
Mid-Canada, ports open all year							
Initial cost	1.933	5.223	7.691	7.003	.764	4.483	.....
Annual cost	1.062	3.089	3.187	2.625	.632	1.595	.....
Mid-Canada, ports open 3 months							
Initial cost	1.950	5.278	7.752	7.055	.774	4.515	.....
Annual cost	1.151	3.376	3.450	2.844	.684	1.730	.....
Mid-Canada, reached by air							
Initial cost	2.264	6.213	8.689	7.906	.882	5.182	.....
Annual cost	1.520	4.582	4.558	3.767	.912	2.299	.....
Arctic, reached by air							
Initial cost	2.819	7.804	10.250	9.335	1.046	6.371	.....
Annual cost	1.860	5.630	5.495	4.544	1.107	2.778	.....

included in budget estimates. Their inclusion, however, facilitates the comparison of air defense costs with those of Strategic Air Command or Tactical Air Command.

TYPES AND COSTS OF STATIONS FOR OVEROCEAN COVERAGE

Because some of the sources of data were outside the Air Force, and because there were no firm plans from which to extrapolate, the cost estimates for overocean coverage were more uncertain than those for ground systems.

Estimates were made for picket ships of the DE(R) class, equipped with AN/SPS-6B or similar radars, and for several kinds of AEW airplanes carrying AN/APS-20 radars. As previously mentioned, there are current plans for using 17-ft antenna dishes instead of 8-ft dishes for AEW if development problems can be overcome. These two types were not differentiated in the cost estimates.

Table 39 shows the cost estimates for various types of stations. The costs are all per picket ship *on station* or per aircraft *on station* and include the costs of back-up pickets and aircraft. Each picket on station was estimated to require a total of two pickets assigned; each B-29 or PO-2W, a total of five assigned; and each AD-3, a total of six. Although there is not much information on which to base an estimate of AEW back-up factors, this choice is possibly optimistic for the B-29 and slightly pessimistic for the PO-2W (which probably can be made to give more flying hours per month). Hence, the costs given here *should not* be used to compare B-29 AEW with PO-2W AEW. They are primarily intended to relate AEW costs to total radar-network costs and defense-weapon costs.

Table 39

ESTIMATED COSTS OF STATIONS FOR OVEROCEAN COVERAGE

(Millions of dollars)

Type of Station	Initial Cost*	Annual Cost*
Picket ship, DE(R)	6.0	2.2
AD-3 AEW	4.5	3.4
B-29 AEW	5.0†	9.0
PO-2W AEW	9.4	9.0

* Costs shown are *per picket ship on station* or *per aircraft on station*.

† This includes modification of existing B-29's but not their original purchase price.

COSTS OF NETWORKS

The total costs of several representative combinations of ground network types and overocean network types were determined, being based on the station costs just given and the numbers of stations. The most promising combinations of the AF, Green, Purple, Brown, and Blue Plans on land and the Able, Baker, Charlie, and Dog Plans over water were costed for each combination of net-

work types. The initial costs were considered to be amortized over a 4-year period, and curves were plotted showing the annual cost plus one-fourth of the initial cost as a function of "cover" (the measure of effectiveness described on page 284). The values of cover were obtained from the intercepts shown in Fig. 86. By plotting the various combinations of ground and sea plans—such as Brown Plan and Charlie Plan—at their cost and cover values, it was clear that certain combinations were not compatible; i.e., their land and sea coverages were out of balance. A smooth curve was drawn, based on the remaining points.

These curves of cost versus cover were the principal results from the radar networks study which were used as inputs in the synthesis portion of RAND's Air Defense Study. Table 40 lists the composition of network types for which curves are reproduced in this chapter. The curves are shown in Figs. 87, 88, and 89. Figures 87 and 88 were plotted using only the cover values for

Table 40

COMPOSITION OF NETWORK TYPES USED IN ESTIMATING THE COSTS OF COVERAGE FOR FIGS. 87, 88, AND 89

Network Type	Station Type	Approximate Spacing between Stations (nautical miles)	Examples of Numbers of Stations	
			AF Plan	Able Plan
High conventional	Group Headquarters and ADCC	...	14	..
	ADDC and GCI	150	91	..
	Mobile GCI	150	16	..
	EW	150	13	..
Gap filler	GF	80	337*	..
Encoding Low-Altitude System	....	80	337*	..
Muldar	Muldar	50	1200	..
	Muldar Control Center	...	24	..
Pickets	DE(R)	150	....	12
B-29 AEW plus pickets	B-29 AEW†	125	....	17
	DE(R)	150	....	12
B-29 AEW plus 12 pickets	B-29 AEW†	125	....	17
	DE(R)	...	....	12
PO-2W AEW plus 12 pickets	PO-2W AEW‡	200	....	7
	DE(R)	...	....	12

* Additional stations *are not* counted at the sites of the big conventional radars which these smaller stations supplement.

† 8-ft antenna dish.

‡ 17-ft antenna dish.

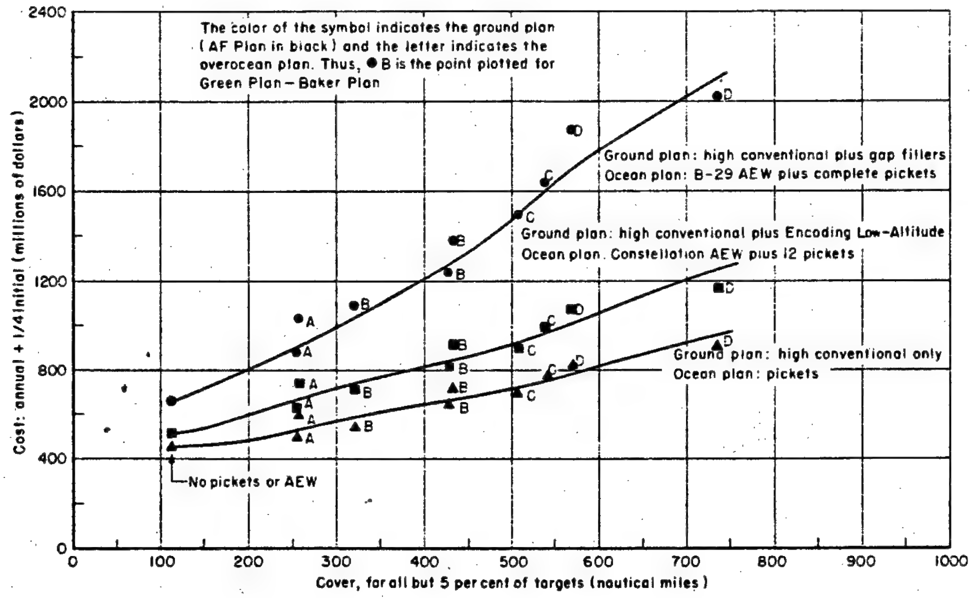


Fig. 87—Cost vs cover—I

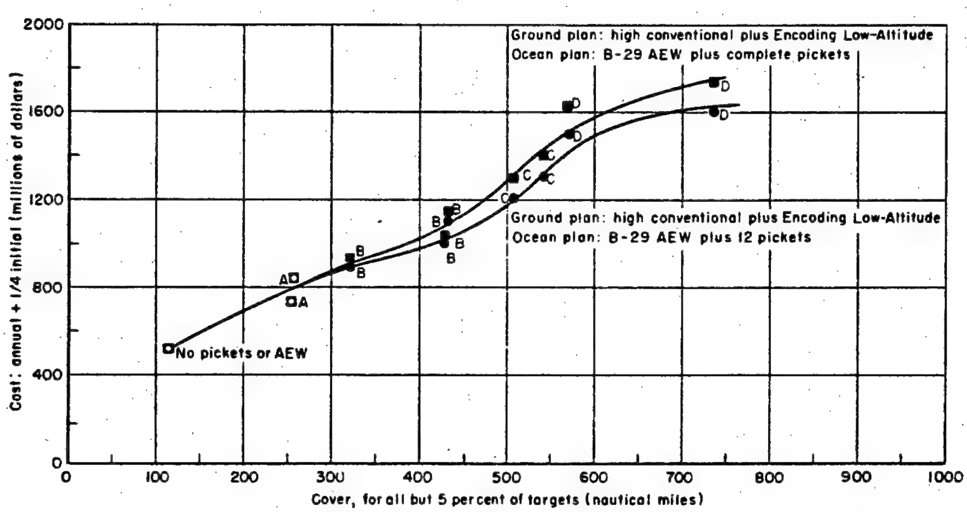


Fig. 88—Cost vs cover—II

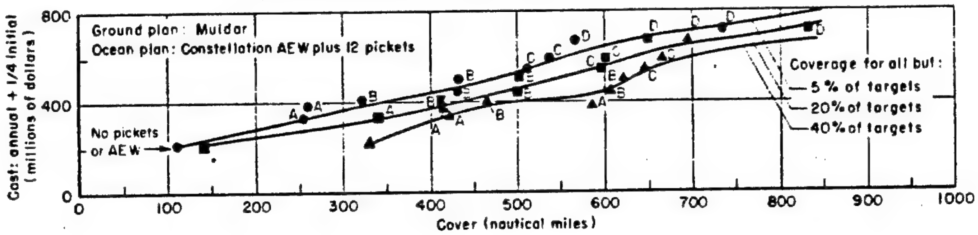


Fig. 89—Cost vs cover—III

"all but 5 per cent" of the targets. These values were read off Fig. 86 where the lower dashed line intercepts the curves. To show the effect of considering "all but 20 per cent" and "all but 40 per cent" of the targets, Fig. 89 presents curves for all three of these levels of coverage.

The costs for AEW coverage depend on spacings which, in turn, depend on the dish size. As noted in Table 40 the costs given here are for B-29's with 8-ft dishes and for PO-2W's with 17-ft dishes. It was not intended that this should imply that a B-29 could not be modified to carry a 17-ft dish nor that the problem of getting the 17-ft dish onto the PO-2W would necessarily be solved very soon. Within the limits of accuracy of these estimates, the B-29 with a 17-ft dish is represented by the PO-2W curves less about 10 per cent of the cost; this reduction in cost is due to the lower initial costs of B-29's if they are modified from existing stocks.

Earlier in this chapter it was stated that AEW coverage would probably need to be backed up with picket-ship coverage, at least in its early years as an operational system. Two degrees of this supplementary use of pickets are shown in these cost estimates—solid coverage and coverage by only 12 pickets.

In the cases of the Encoding Low-Altitude System and Muldar, it should be noted that both are manifestations of the same basic philosophy—to obtain low-altitude coverage by means of a great many small radars which are as automatic as possible. The particular curves shown in Figs. 87, 88, and 89 are for an 80-mile spacing of the Encoding Low-Altitude stations and for a 50-mile spacing of the Muldar stations, but neither system is limited to these values. (Also shown is the "brute-force" method of obtaining low-altitude coverage, by using fully manned gap fillers of the AN/TPS-1D class. With cumbersome present-day data handling, it is not likely that spacings closer than 80 miles could be used in this system.)

Also reflected in the curves are the higher annual costs attributed to the Encoding Low-Altitude System when compared with Muldar. The primary

reason for these higher costs was that the former stations, as pioneer attempts along this line, would require more maintenance men. The annual costs for Muldar are quite optimistic for the all-altitude version of this system, and are presented as representing a lower limit and goal for radar-network costs during the next decade. *Separate estimates were not made for low-altitude Muldar and all-altitude Muldar* because of the uncertainties involved in both. (All-altitude Muldar may cost appreciably more because of its height-finding requirements.) In actual practice, if all three of these low-altitude types reach the field, they will probably be used in various parts of the network simultaneously during most of their useful lives.

PROGRAMMING AND SALVAGE VALUE

All the radar networks described in this chapter are so extensive that it would take several years to build them, and their total initial costs would have to be spread over several fiscal years, even with present expanded budgts. For many decisions it is more important to know how much must be spent in a *given* year than to know the recurring annual cost and total initial cost. This requires that costs be "programmed" over the years. If the program is realistic, it also tells how long it will take to obtain a certain network.

In RAND's Air Defense Study, conventional high-altitude and gap-filler costs were roughly programmed, using the scheduled rate of progress of the AF Plan as a standard.[26] (That schedule has since proved to be overly optimistic.) Table 41 shows some of the results of the conventional high-altitude

Table 41

COSTS BY FISCAL YEAR OF PROGRAMMED CONVENTIONAL HIGH-ALTITUDE RADAR NETWORK

(Millions of dollars)

Fiscal Year	Extent of Coverage				
	AF Plan	Green Plan	Purple Plan	Brown Plan	Blue Plan
1951	262	262	262	262	262
1952	613*	613	613	613	613
1953	302	456*	611*	611	611
1954	...	359	416	574*	762*
1955	...	...	...	475	542

* Installations completed in this fiscal year; costs for the following years are entirely annual costs.

network programming. The values are in millions of dollars and are the sums of initial-type and annual-type costs.

In addition to considerations of programming, decisions to build new types of networks should involve the possibilities of re-using items purchased for the old network. This results in a certain "salvage value" for the old network. These savings were not taken into account explicitly in the study as either debits or credits. A brief look at the re-use possibilities of Muldar, one of the most pertinent cases, indicates that initial costs may be cut by about 25 per cent through the salvaging of installations, organizational equipment, and training.

The two factors just discussed, together with other similar factors, indicate that the cost curves are far from being the whole story of the comparative effort required to achieve various networks. It should also be pointed out in this connection that the addition of one-quarter of the initial cost to the annual cost, i.e., amortization over 4 years, may not be quite right for some cases. Originally, a 7-year amortization was used for some of the stations, but after considering the changing development trends, and because the initial costs were relatively small anyway, it was decided to use 4-year amortization throughout, as was done in the weapon-system costing.

This brings up an important point. *Annual costs are dominant in almost every case. Furthermore, the most important components of annual costs are those which depend on the number of personnel.* The most direct way to reduce the cost of a radar network, then, is to arrange it so that it can be operated by fewer people.

X. Tactical Usefulness of Radar Coverage

The minimum objective in laying out a radar network is to provide at least enough time after bomber detection to allow all the necessary defense actions, directed toward the bomber kill, to occur with a satisfactory probability before the bomber reaches his bomb-release line. There are three main tactical advantages which accrue to the defense if the extent of radar coverage is increased above this minimum:

1. As the time allowed for the defense actions is increased, the probability of the successful completion of these actions is also increased. As a simplified example, suppose that there is so little time that an interception cannot be made if an interceptor takes 5 minutes to scramble, instead of two. Added radar coverage would increase the number of interceptions.

2. If an interceptor is used to protect targets which are not in the immediate vicinity of its air base, it requires extra travel time in order to reach the interception point. This is translated into a need for extended radar coverage. As the value of the "protected radius" increases, more targets are protected, and more combat radius is required of the interceptor; consequently more coverage is demanded of the radar network.
3. Much of the initiative in an air defense operation rests with the offense. In order to provide protection against possible enemy feints, the defense must either reserve a fraction of its force or have more extensive radar coverage. Similarly, earlier or more extensive information on the pattern of attack can eliminate some of the effects of tactical surprise.

In each of the above cases there are certain advantages in having more extensive radar coverage, but because of the extra effort and extra difficulties involved in obtaining this coverage, it is necessary to find the point of diminishing return. Some of the ways in which RAND's Air Defense Study tried to balance the tactical gains against the cost of extending the radar networks will be described below. Some of the work cannot be fully described in this chapter because it is dependent on the target-selection strategies and protected-radius computations, which will be discussed in Part II of this report.

TIME AVAILABLE FOR DEFENSE ACTIONS

If all the separate times required for the various precombat defense actions —identification, evaluation, scramble, climb, and horizontal flight—were subtracted from the time that it takes the bomber to fly from the point where it is detected to its bomb-release line, the remainder would be the time available for combat. Most previous calculations of this type have used a single *expected* value for the various times involved, but exercises have shown that there is a significant distribution of times about this value. Therefore, where the spread of values was significant, the distribution, rather than the expected value, was used in the computation of available combat time. Combat time as used here means the time from the end of the AI homing phase until the bomber reaches the bomb-release line. An interceptor armed for a single pass could use this time to make repeated attempts to convert its AI contact into a firing pass; an interceptor armed for several passes could make repeated attempts until its armament was expended. The time remaining for combat

can be found from the following equation:

$$t_c = \frac{R_t - \overline{LD} - t_m v_b - \dfrac{v_b}{v_f}(\overline{LD} - z)}{v_b\left(1 + \dfrac{v_b}{v_f}\right)},$$

where t_c is the available combat time,

t_m is the sum of identification, evaluation, scramble, and AI radar homing times,

R_t is the range from radar detection to target,

$\overline{LD}$ is the local-defense zone in which combat is prohibited (or it may be considered a glide-bomb release line),

v_b is the bomber speed,

v_f is the interceptor speed,

z is the equivalent distance from the target to a hypothetical fighter field located on a line from bomber to target. The hypothetical field is in the location that would allow interceptions at the same point as the real field. (This quantity is positive for fields ahead of the target.)

A numerical example of the increase in kill potential[27] with an increase in combat time was illustrated in Fig. 40 (page 132) for the generalized interceptor versus the Stalin bomber. If no constraint is placed upon the interceptor design, the topmost curve at any combat-time value can be used. A similar curve was drawn for the earlier one-pass interceptors, the F-86D and F-94D, but in terms of the probability of AI detection and conversion versus combat time.

Using the method described in RM-518,[28] together with the appropriate radar-range corrections to the cover, estimated times for the defense actions, and the assumed airplane speeds, it was possible to determine the available combat time in terms of its mean and standard deviation.[29] Since the coastal targets are

[27] Defined on page 126.

[29] In all but a few cases, the approximation was made that distributions were normal. The quantities used in these calculations were assumed to have the following means and standard deviations:

$t_m = 13 \pm 5$ minutes, being made up of 7 ± 4 minutes for identification and evaluation, 3 ± 2 minutes for scramble, and 3 ± 2 minutes for AI homing;

R_t = values taken from the distributions of Fig. 85, with corrections for the radars involved;

$\overline{LD} = 30$ miles;

$v_b = 6$ miles/minute for the TU-4 and 8.3 miles/minute for the Stalin;

$v_f = 1.2\ v_b$ against the TU-4 and $1.0\ v_b$ against the Stalin;

$z = 0 \pm 20$ miles (from measurements on a map of East Coast targets and fields).

most pertinent in this case, only the least-covered 28 per cent of the targets were included in finding these values. Using the kill potential versus combat time curve of Fig. 40, or the probability of detection and conversion versus combat time curve mentioned above, the effects of coverage extent were found in terms of tactical significance. The results are given in Table 42.

Table 42

EFFECT ON THE AIR BATTLE OF VARIOUS EXTENTS OF RADAR COVERAGE

Radar Network	F-86D or F-94D vs TU-4		Generalized Interceptor, Equipped with 12 MX-904 Missiles, vs Stalin Bomber	
	Combat Time (min)	Probability of Detection and Conversion	Combat Time (min)	Kill Potential*
AF Plan, no pickets	(†)	0.75‡	2.7 ± 4.0	327**
AF Plan, Able Plan	13.9 ± 7.0	0.92	8.1 ± 5.4	468
Green Plan, Able Plan	17.5 ± 9.6	0.92	10.7 ± 7.2	510
AF Plan, Baker Plan	20.5 ± 6.6	0.99	12.9 ± 5.1	598
Green Plan, Baker Plan	28.8 ± 7.6	1.0	18.9 ± 5.8	672
Purple Plan, Baker Plan	29.1 ± 7.7	1.0	19.1 ± 5.8	675

NOTE: Bombers enter radar network at 30,000-ft altitude. Values shown are based on the 140 targets nearest the edge of radar coverage out of 507 targets in the ZI.

* The interceptor design was not considered to be fixed in this case, and the best design for a given combat time was assumed.

† This distribution was non-normal and can be approximated by two equally likely normal distributions of 9.6 ± 3.4 minutes and 4.9 ± 4.3 minutes.

‡ Against a 5000-ft attack, this value would be 0.36.

** Against a 5000-ft attack, this value would be 203.

COVERAGE REQUIRED VERSUS COMBAT RADIUS UTILIZED

An interceptor of 300-mile combat radius cannot be utilized at that distance from its base in the usual air defense ground-scramble operation unless radar detection of the bomber occurs soon enough to permit the required fighter travel. A typical case of lateral deployment of an interceptor is shown in Fig. 90. In this figure the interceptor flies out x miles, engages in combat for 10 minutes, and returns y miles. A local-defense zone of 30 miles is assumed, which means that aerial combat must finish before the bomber enters that zone.

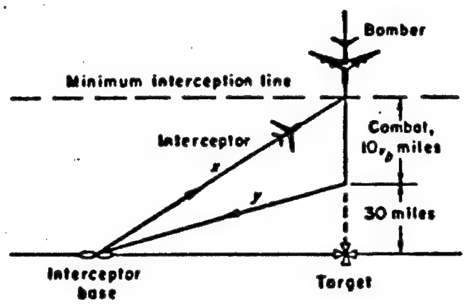


Fig. 90—Lateral deployment of interceptor

The target and interceptor base are assumed to be on a line normal to the bomber track, as shown. The problem is to find the additional radar coverage required in this case, complete utilization of combat radius being assumed, as compared with the case in which the interceptor base and target are effectively in the same place.

In terms of the interceptor and bomber characteristics, the radar coverage, R_l, required in addition to that necessary for the defense of the nearest targets was found to be:

$$R_l = \left[R_c + \frac{5v_b(30 + 5v_b)}{R_c} - (30 + 10v_b) \right] \frac{1}{\eta_c},$$

where R_c is the interceptor combat radius, equal to $x + y$ of Fig. 90,
v_b is the bomber speed, in miles per minute.
η_c is the ratio of interceptor speed to bomber speed *during cruise out* (not in combat).

The additional radar coverage required, as found by the above method, is shown in Fig. 91*a* for TU-4, Stalin, and Lenin bombers and the appropriate interceptors. These results, together with radar and interceptor cost estimates and computations of the targets protected for various combat radii, were used in finding the over-all effect of varying combat radius. This part of the study will be described in Part II of this report. It will suffice to say here that it appears to be economical to increase the radar coverage somewhat to permit lateral deployment of interceptors and that this was taken into consideration in reaching the conclusions regarding AEW and picket-ship coverage given in Chap. 2.

COVERAGE REQUIRED FOR PROTECTION AGAINST FEINTS

It is possible for the commander of an interceptor force to be tricked into committing his force in a pattern planned by the offense, e.g., to make more attacks on early bombers carrying few bombs, and possibly dropping chaff, than on later bombers carrying many bombs. This can be obviated by increasing the radar coverage until a picture of the air situation is obtained which is extensive enough to allow a uniform commitment of defense forces.

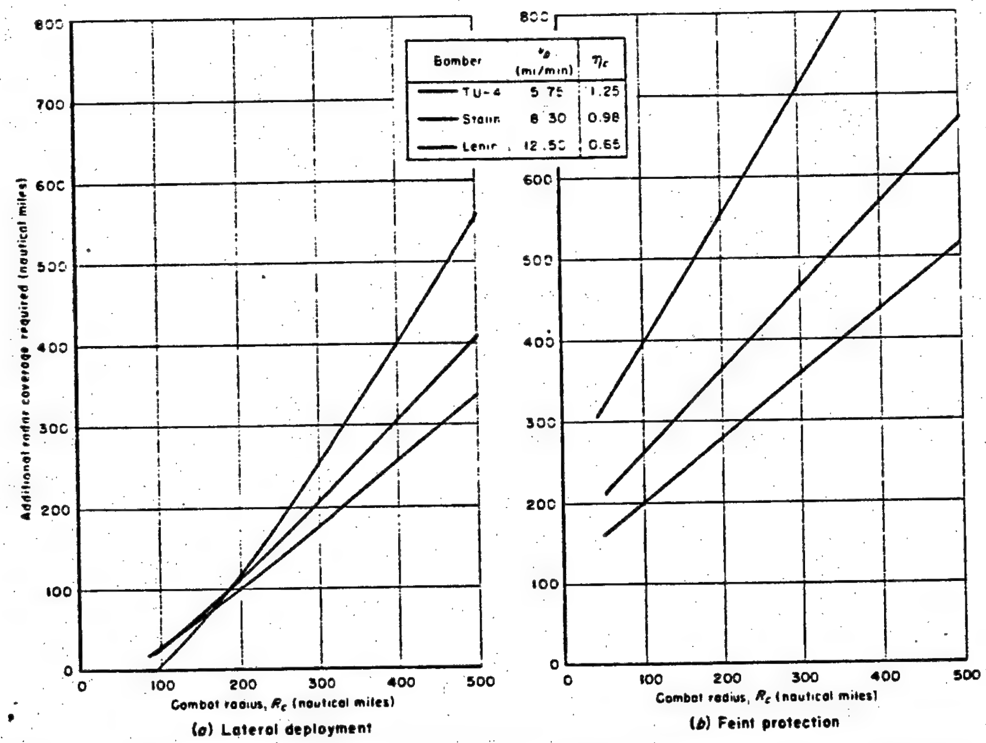


Fig. 91—Additional radar coverage required for lateral deployment and feint protection

It was assumed in RAND's study that the worst situation for the defense would be one in which a second bomber element entered the radar coverage just after the interceptor force had fired its armament load at the first bomber element. It was assumed that movement during combat was neither toward nor away from the interceptor base. A time allowance of 20 minutes was made for landing the interceptors, rearming them, and getting them into a status equivalent to that which existed prior to the attack on the first bombers. The additional radar coverage required, R_f, would then be

$$R_f = \frac{R_c}{\eta_c} + 20v_b,$$

where the notation is the same as that given above. The resulting values of additional coverage required for protection against feints by TU-4, Stalin, and Lenin bombers are shown in Fig. 91*b*. The magnitude of these values indicates that some other way of protecting against feints would probably be cheaper or more practical. After consideration of the relative costs of more cover or more

interceptors, it was decided *not* to assume the purchase of the necessary cover in the synthesis part of RAND's Air Defense Study. (The conclusions in Chap. 2 *do not* suggest coverage for this purpose.) Instead, the protection radii of interceptors protecting coastal targets were reduced, and, in addition, only two-thirds of the available interceptors were assumed to enter the initial air battle, the remaining one-third being reserved for closely following bomber attacks. When this two-thirds commitment factor near the coast was averaged over all the ZI, a factor of 0.85 resulted. This was the F_{sc} by which kill potential was multiplied, as discussed in Chap. 7 (page 126).

CHAPTER 12
TECHNICAL FEASIBILITY

Brief Descriptions of Some Ways of Doing Critical Jobs

Several times in the course of RAND's Air Defense Study it was apparent that the ability of the United States to solve a development problem could make a decisive difference in defense effectiveness. In some cases, as for example in the development of AI radar for high-altitude interception, it appeared that the continuation of present programs and the present degree of development emphasis had a good chance of providing adequate equipment at the desired time. In other cases the prospect seemed quite doubtful. As pointed out in Chap. 3, numerical calculations were undertaken in the Defense Systems Analysis assuming these problems to be soluble by some given year. The numerical results then furnish an index to the possible payoff if the problems are in fact solved by that time. Considering both the implications of the numerical results and the practical problems involved, RAND came to the conclusions given in Chap. 2. Thus, the numerical analysis proved to be quite useful in focusing attention on critical areas in the development of equipment and tactics.

In making exploratory investigations of some of these critical problems, it was found possible to make preliminary design studies. In other cases, particularly on certain airplane problems, it was felt that this work could be done more appropriately by the aircraft companies or other contractors. It is RAND's belief that much of the real payoff of its defense study lies in the uncovering of these critical problems and will come as a result of a USAF follow-through to see that promising avenues of attack are exploited. Toward this end there is continuing work in progress at RAND on many of the problems discussed below.[1]

[1] The selection of topics for discussion in this chapter should not be regarded as an enumeration of the important problems of this type. They are simply those problems about which there was something new to report at this time.

I. Supplementing the Radar Network with Low-Altitude Coverage in the Near Future

An important conclusion of RAND's defense study was that the Soviet Long Range Air Force (LRAF) might find a low-altitude attack both feasible and attractive and that the United States is ill-prepared for such an attack. In addition to having effective weapons at low altitude, we must also have a data-handling network to provide information for the assignment and control of defense weapons. In a later part of this chapter, a Muldar radar technique to provide low-altitude data will be described. However, this kind of radar probably will not be operational until after 1956. The problem of obtaining defense at all altitudes in the interim period is both difficult and acute. RAND has proposed the following five steps, which might begin to have an effect in 1954. The first two steps will be discussed in this section.

1. *Put together a system of small radars which could be tied into the existing big radars* to supplement their coverage at low altitudes. The devices for gathering, transmitting, and presenting the added data must be drawn largely from completed developments. The techniques should cause a minimum disruption of the present organizational structure, making use of existing equipment and the past training of personnel.
2. *As a secondary program, increase the effectiveness of the Ground Observer Corps* by using some mechanical devices, increasing the availability of communication channels, and, perhaps, rearranging the pattern of data flow. The GOC program would be a hedge against delay in the radar program and would be a useful adjunct to the network in certain locations.
3. *Begin an expedited procurement and installation program* as soon as demonstrations and tests indicate reasonable promise for the above techniques. It will probably be necessary, in some cases, to subordinate performance and economy to early accomplishment. At this stage the phasing-in of the next generation of low-cover radars must be borne in mind because there is a considerable prospect of savings in the re-use of older installations.
4. *Obtain as much low-altitude performance as possible from present AI radars without moving-target indication (MTI).* On the basis of a few tests at Air Proving Ground, it appears that the AI radars now being installed are capable of limited effectiveness in two-place inter-

ceptors down to about 1000 ft. Extra time and special tactics are required. These tactics should be developed by extensive testing in various terrains and be adopted by operational units through training programs suited to the locality. By day, when bombers might fly lower than 1000 ft, the interceptors could rely more on visual sighting and, in most cases, would be aided by a good knowledge of their home terrain.

5. *Improve the AI capability of the interceptor.* While satisfactory airborne MTI, as presently envisaged, may not be operational during this interim period, there will probably be several relatively simple techniques for improving operation in the presence of clutter. In addition, the possibilities of passive homing on the bombers (especially if the enemy habitually uses navigational radar) or the use of infrared should be exploited if tests show the utility of these techniques.

If these five steps prove workable, and it now appears that they may, then the interceptor can begin to have effectiveness as a low-altitude weapon by about 1954. If not, the United States must either spend exceedingly large sums on strong low-altitude gun defenses or be susceptible to a very damaging attack, the potential destruction of which grows year by year.

GENERAL REQUIREMENTS FOR SUPPLEMENTARY COVERAGE METHODS

Some general comments about ways of carrying out the first two steps given above can be made before going into the exact methods which RAND believes most promising.

Each large radar of the types now being installed throughout most of the United States has a GCI control room associated with it. It is proposed to supplement the existing network by gathering the missing low-altitude data within the primary area of responsibility of each large radar and feeding them into this control room. It would be highly desirable to convert the low-altitude data into a form similar to that produced by the large radars so that they can be used, with a minimum of change, with existing data-handling and control techniques.

Radar or visual sighting by interim-period interceptors can nearly always be done at ranges of the order of 5 miles. From this it is estimated that a 10-sec data interval and a resolution of about 1 mile in each coordinate, with corresponding accuracy, would ensure a fairly high probability of acquisition of

near-future bombers. This accuracy requirement applies to height measurement and is easily met above about 5000 ft by the big-radar facilities. If we can assume that any target[2] seen by the auxiliary low-altitude system, but not seen by the big radars, is between 0 ft and 5000 ft, then no further height-finding is needed to meet the required standard of accuracy.

In the long run, the inclusion of low-altitude data in the GCI control room might not increase the data-handling load of the room because all-altitude radar cover would probably permit the use of belt identification techniques. Identification could then be performed in a belt where the commercial traffic was low. Once identification was made, enemy aircraft could be tracked continuously into the interior, where the traffic was dense. Commercial traffic would be ordered to land or to fly in directions away from the incoming raid, but detailed handling of their tracks could be minimized. As far as handling tracks of bombers and interceptors is concerned, there would be no reason to expect a larger load because more air space was being covered—the stockpile of enemy bombers and the number of our fighters would be unchanged.

DATA GATHERING BY GAP-FILLER RADARS

The RAND study found a suitable method of obtaining additional low-altitude coverage. By this method, three to ten small radars, each having a range between 25 and 50 miles, would be associated with each large radar. Figures 92 and 93 show how these radars might be sited. The radars would feed data into the GCI *over telephone lines* (or equivalent radio channels), using one of several possible data-compression techniques. At the GCI station, the data would be assembled in the form of a large picture, corresponding to the geographical position and coverage of the ensemble of radars, and would then be transformed to give the appearance of having come from the video signal of the large radar. By this scheme, each director and B-scope operator could see the low-altitude data as well as the high-altitude data, or he could choose to view either separately. Furthermore, each director could use his conventional console for either type of data, displacing or enlarging the picture in the manner generally used for control purposes.

A number of radars can be used for the gap-filler function. These radars need only a fan beam covering up to about 5000-ft altitude and would transmit

[2] *Target* is used in this chapter to mean an aircraft or missile seen by a ground radar or seeker. It is unfortunate that there is not some equally useful synonym, because *target* is also used in this report to mean the United States industries, population centers, etc., which are possible objects of bombing attack. In Chaps. 1 through 11 an attempt was made to restrict *target* to the latter meaning, except where the context left no room for doubt.

only azimuth and range data. They should, however, have the best MTI equipment available, since good MTI is essential for any low-altitude radar application. A number of radars, such as the ASR-1, ASR-2, ASR-3, AN/CPN-4, and AN/CPN-18, have almost the desired characteristics. The ground-clutter rejection of these radars is not so good as is desired, but it is probably as good as can be obtained at present and is adequate for most regions of the country. In addition, these sets appear to be well engineered and to give reliable operation.

Although the bandwidth of the video output of these sets is of the order of 1 or 2 Mc, the required data can be transmitted in a much narrower bandwidth. If the radar is rotating once every 10 sec and has a beamwidth of 3°, only 12 range sweeps per second need be transmitted. If a 30-mile range base is divided into 30 one-mile range-resolution blocks, then only 360 pps need be transmitted. Assuming that 2000 pps can be sent over a telephone line, a margin of safety can be used. For example, data can be sent with a resolution of about one-third of a mile in range and 2° in azimuth, provided the data can be reduced to the proper form.

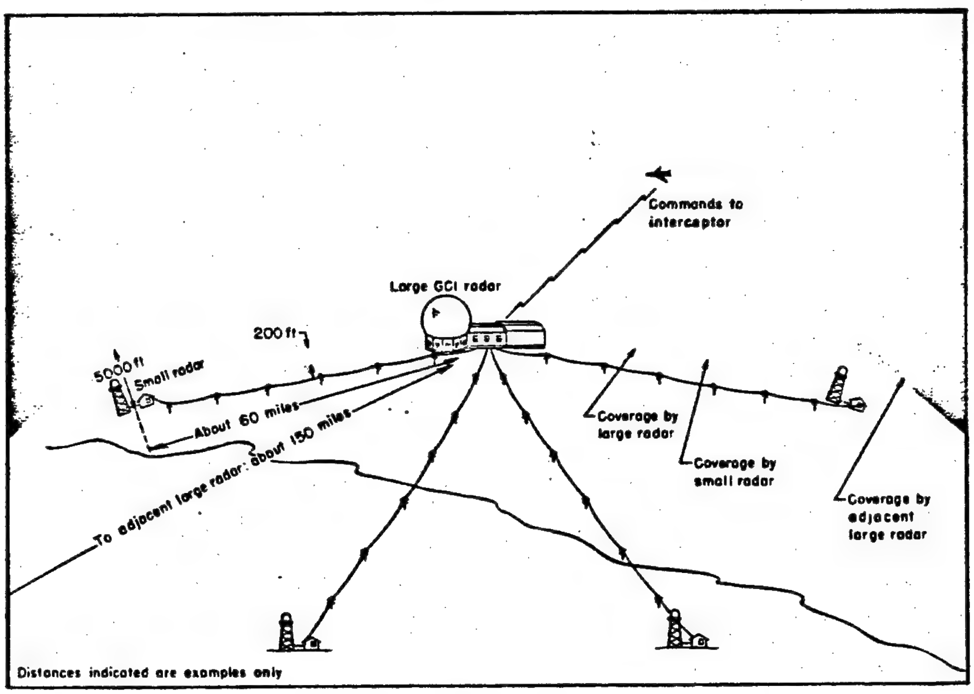
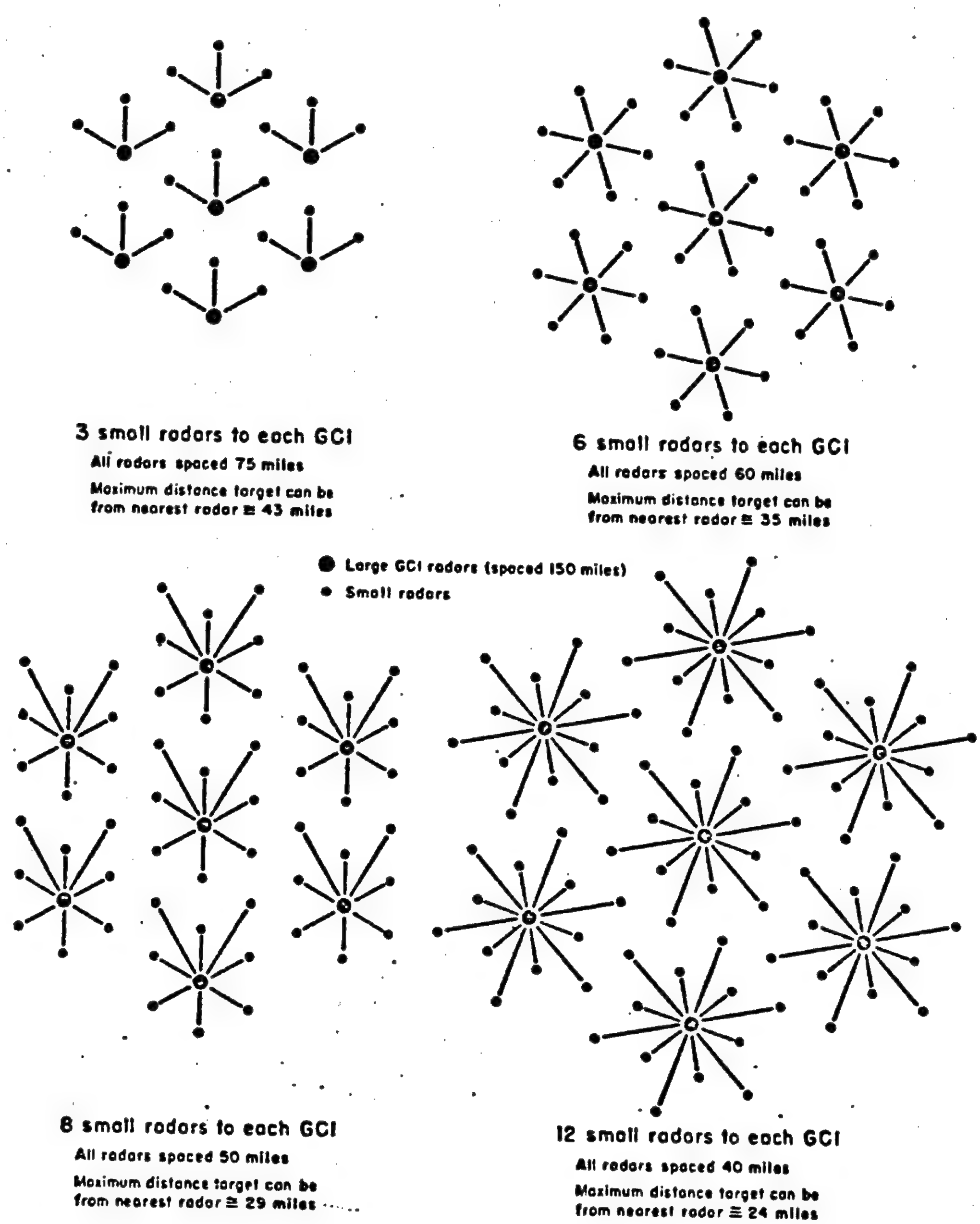


Fig. 92—Radar deployment for supplementing high-altitude coverage



The lines show possible ways of connecting the small radars into the network. In real installations, the symmetry of the patterns will be distorted to account for terrain variations.

Fig. 93—Some possible layout patterns for various ratios of small to large radars

One of several methods that are both simple and feasible for doing this is to use a linear-sweep oscilloscope in which the radar video intensity modulates the beam. The tube phosphor persistence can be used to integrate the returned signals, and the signals can be read off at a slow rate by rotating a disk, containing a slit, in front of the scope. If a photocell is used behind the slit, its output will be proportional to the radar data, but the rate at which the output appears will be a function of the disk speed only. An intensity-modulated circular range trace on the scope would simplify the scanning process. The scanning disk could then be mounted coaxially with respect to the center of the circle, as shown in Fig. 94. The Rafax scanner constructed for the Rome Air Development Center is such a device.

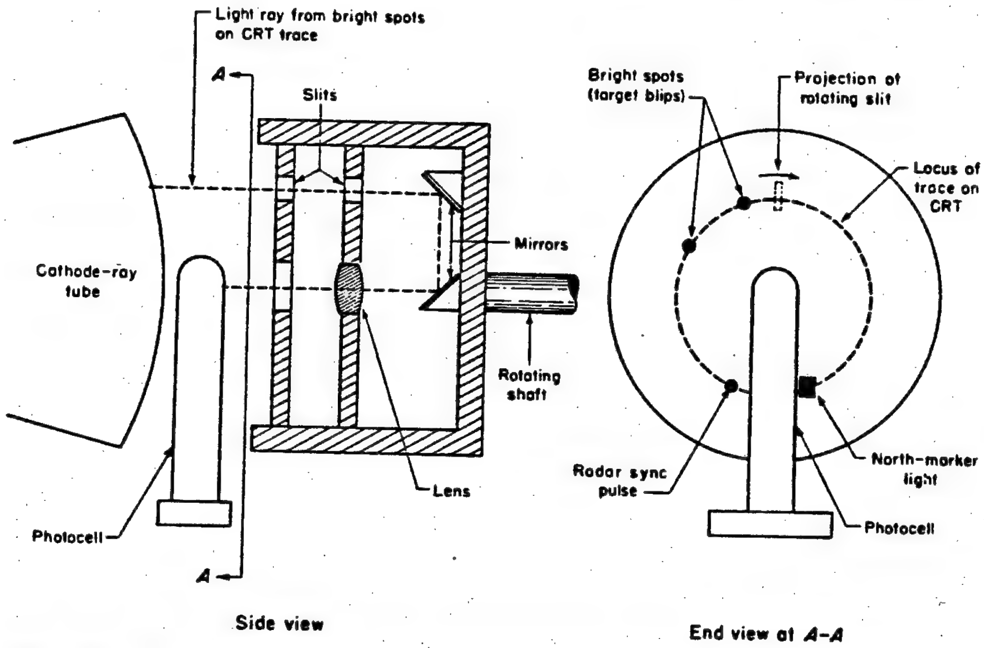


Fig. 94—Schematic drawing showing data encoding by Rafax scanner at small radar

If this scanner and the radar antenna are rotated by synchronous motors driven by the same power source, the repetition period of each range trace can be integrally related to the azimuth rotation period of the radar antenna. A synchronizing pulse can be sent at the beginning of each range sweep so that the range-sweep and azimuth-rotation information can be re-created at the other end of the telephone line. It then becomes possible, by transmitting only

these synchronizing pulses and the compressed video data from the scanner, to reproduce the PPI picture at the receiving end.

A north marker should also be transmitted to guard against the possibility of loss of synchronizing pulses because of line interruptions. The marker can be generated by a light turned on by a microswitch connected to the radar antenna. The light can be placed at the end of the sweep on the cathode-ray tube.

The data-encoding equipment at the small radars is shown in schematic form in Figs. 94 and 95.

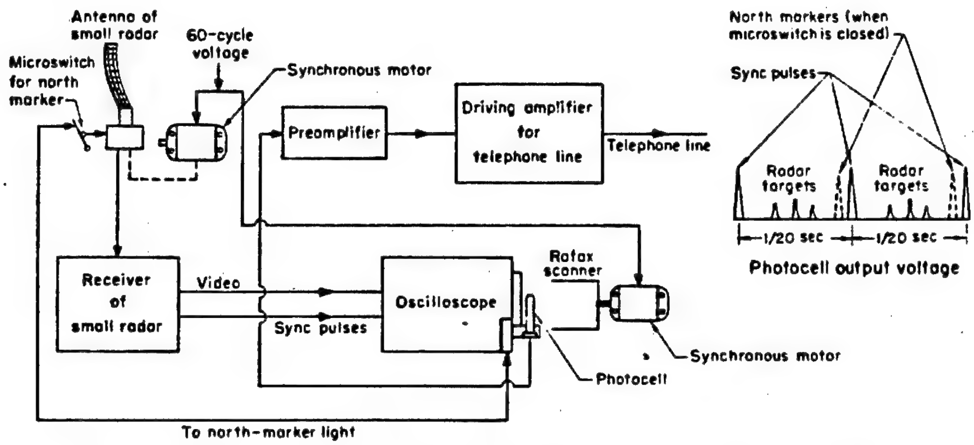


Fig. 95—Schematic drawing of data-encoding equipment at small radar

At the receiving end, the synchronizing pulses can be detected and used to generate the range sweeps and to produce a 60-cps voltage which may be obtained by taking a suitable harmonic of these synchronizing pulses. The 60-cps voltage can then be used to drive a synchronous motor which rotates the deflection coil of the remote PPI tube. The north marker can be aligned manually by rotating a differential in the PPI drive.

Another method for reducing the radar video data to the desired bandwidth is to use a Vidicon television camera for viewing a range trace or a B-scope presentation and then to sweep the Vidicon at the desired slow rate. Still another way is to use a Graphecon tube, which has two electron guns, in a similar fashion. At present, however, the mechanical method and possibly the Vidicon appear to be the simplest and most feasible. The Vidicon or Graphecon give better integration than the mechanical scanner because, with the mechanical scanner, it is difficult to obtain cathode-ray-tube phosphors having the desired decay time, whereas the Vidicon and Graphecon can store and erase

data in a manner that is nearly ideal for integration. However, they may prove to be more complicated and less reliable in operation.[3]

With either the Vidicon or the Graphecon, it is also possible to encode by viewing a PPI presentation and sweeping it with conventional television scans using reduced sweep rates. This is possible because either of these two tubes stores the data until the data are read, so that the reading beam need not follow directly behind the PPI writing beam, and it is not necessary to depend on the relatively poor storage obtained by phosphors such as the P7. This technique, while it would not require that the radar antenna be driven in synchronism with a rotating scanner, would add a delay to the data, varying from 0 to 10 sec, because the data would be generated in polar coordinates and read in rectangular coordinates.

By using any of the techniques mentioned above at the receiving end, a PPI picture can be obtained on a separate scope for each gap-filler radar that is to be used with a large radar. It is desirable to combine all of these pictures into one large picture corresponding to the coverage of the large radar. Each PPI can be arranged spatially to correspond to the position of the radar from which its data are derived with respect to the position of the large set. The fact that the data from different sets might overlap physically prevents this from being done directly, since it is impossible to overlap PPI tubes. To avoid this difficulty, the tubes can be divided into two groups by placing every other tube in its correct position in one group and the others in their correct positions in the other group and using a half-silvered mirror to view them all. The images can then be placed physically as desired, the necessary overlaps being included. The receiving-end equipment is shown schematically in Fig. 96 for the case where six small radars are connected into one large radar.

It is possible to view this composite picture either with a Vidicon television camera or with a rapid-development photographic camera and obtain an integrated picture. The Vidicon television camera appears to be the simpler of the two and to involve the least time-delays if it proves feasible. The sweeps of the television camera would be altered from the usual television sweeps to a polar coordinate sweep so that the sweep would rotate in synchronism with the large-radar scan. The Vidicon output would then be a video signal, similar to that of the large radar, that could be mixed with the output of the large

[3] Digital compression techniques and microwave video links might be used as an alternative method of data transmission from the small radars. These techniques will not be discussed here, however.

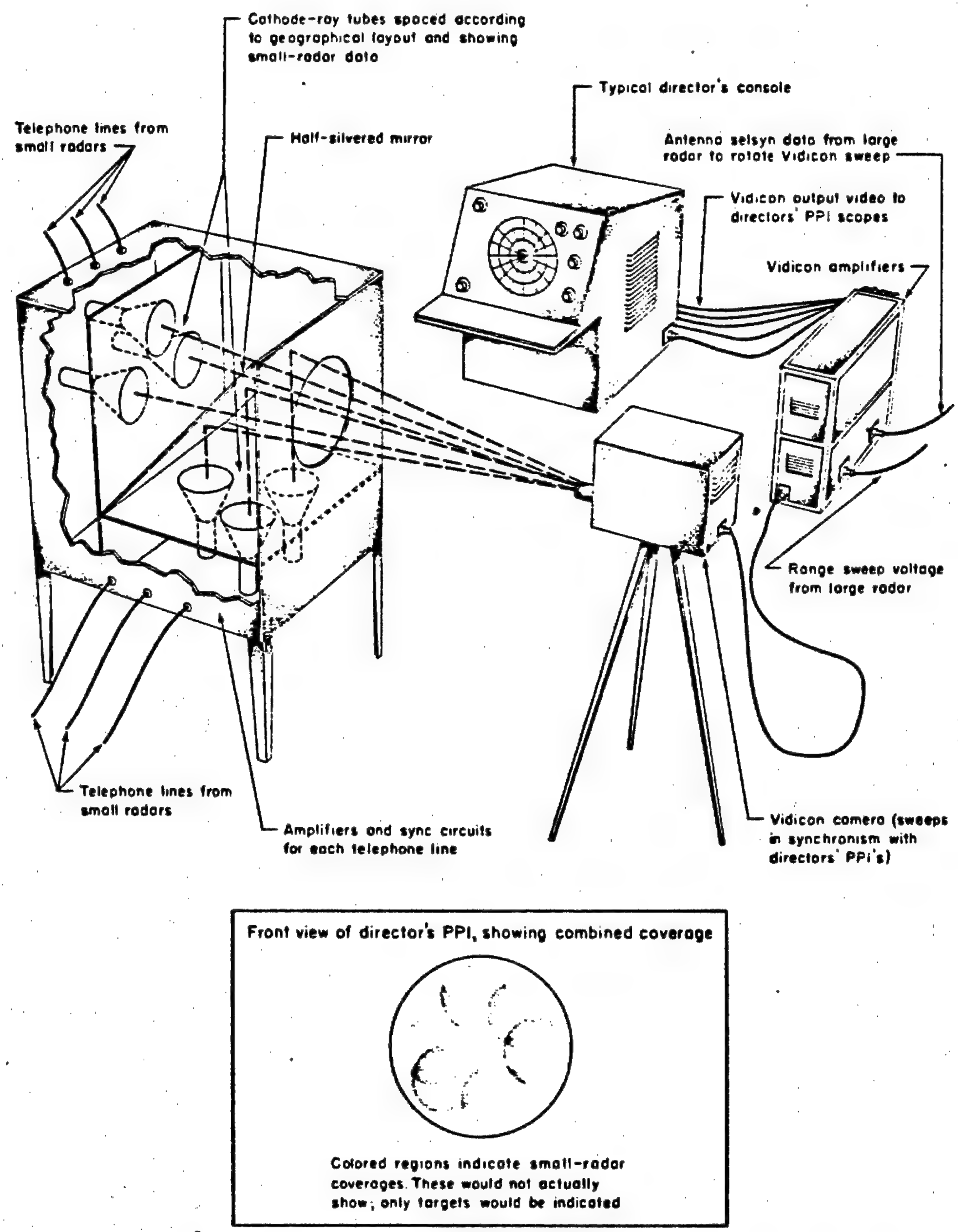


Fig. 96—Possible equipment layout for combining signals from small radars and injecting them into directors' PPI scopes

radar, if desired, and viewed on a conventional GCI console without requiring any changes in that equipment.

The resolution of the Vidicon is about 400 lines and the primary region covered by a large radar is about 180 miles square, which gives a resolution of the order of ½ mile. It would be desirable to have better resolution, but 400 lines would probably be adequate. Although there are television tubes that have better resolution, they have been rejected because they do not have other necessary properties. For this application, it is necessary for the viewing tube to store data for at least 10 sec before they are removed by the reading beam, because the data arrive continuously from the small sets, whereas they are read only when the main radar beam is pointing in the direction from which the data are coming. Some signals are thus read immediately and others are not read for 10 sec after they appear. In addition, the tube must have sufficient sensitivity, be simple to operate, and remain in proper adjustment for long periods of time. All of these considerations favor the Vidicon as being the best choice for this application.

If the Vidicon should prove inadequate, it would be possible to use TPI techniques, i.e., a photographic camera to photograph the composite picture once every 10 sec. After development, which can be done in 4 sec or less, this picture can be video-mapped, using a PPI tube and a photocell, so that the data can be placed in the video of the main radar.

By some combination of the schemes mentioned above, it appears feasible to use existing radars and equipment to obtain low-altitude data and to present the data in a form that can be used as the high-altitude data are used, and to do this without altering the GCI equipment or operation. This would be the most important step toward all-altitude capability for our interceptors in the near future.

GROUND OBSERVERS

As presently organized, the Ground Observer Corps (GOC) provides essentially no capability for interception control. This is because of the sporadic coverage afforded by ground observers and the long time-delays (of the order of 3 minutes) involved in getting the information to the GCI control room where it can be used. The British try to overcome this latter difficulty by using controllers at the GOC filter centers, and even allow ground observers to control fighters directly. In this country, because the network is less closely tied together than it is in England, and because we have had less experience

with the GOC, such techniques would appear to lead to confusion and could not be depended on.

The GOC, however, could be made effective if the coverage were greatly increased by an effective morale-building and recruitment program, by paying observers or by using military personnel in regions where volunteers could not be obtained, and by modernizing the means of data transmission. A brief study has been made of ways to obtain the data more rapidly and with greater accuracy.

The use of conventional voice communication and conventional filter centers does not appear to be satisfactory because too much time is consumed and too many lines and operators are required. It might be possible, however, to provide each ground observer with an encoding device. This might involve the use of a box with push buttons or the dialing of a code on a standard telephone instrument. The data could then go over private lines to an exchange, possibly through the use of a subchannel. RAND's brief study of this problem indicated that many of the existing telephone lines to GOC posts are of unpredictable quality. In regions where this is a prevalent condition it might be preferable to have the first mechanization at the local telephone exchange, employing full-time special operators to encode the voice messages.

If desirable, data from the GOC posts or special operators could be stored on a tape, together with data from other posts or operators, until they could be read off and sent at an optimum speed directly to a GCI station. The function of the filter center might be simplified considerably if the flow of data could be speeded up. It would be very desirable to filter as a parallel monitoring function, if possible, rather than to use the present series method in which all data are processed. (The "parallel method" would pass data which are essentially right without processing, would suppress spurious and unwanted data, and inject omitted data.)

At the GCI, the data from all exchanges reporting in could be stored and read off by a digital-to-analogue device and presented on a cathode-ray tube. The procedure described for the low-altitude radars could be used for converting these data to video signals to be used by directors. The ground observers in this case might transmit only position data, with approximately 1-mile resolution, so that the data would resemble those obtainable by radar. They could, however, send additional data indicating positive identification of aircraft as friendly or enemy, but the presentation of such additional data might result in considerable additional complexity.

RAND's consideration of GOC effectiveness was quite brief. Whether or not further study will indicate that the methods suggested above are the most practical, there is little doubt that big improvements in GOC data can be made soon. There are now at least two projects which show promise. It should be emphasized, however, that *any system for this use should be designed to facilitate control of fighters,* preferably by getting the GOC data into a form that can be put on the directors' PPI scopes.

II. The Muldar System

The low-altitude coverage methods just described for use during the interim period (until about 1957) were primarily planned to achieve an expeditious solution. They will become increasingly inadequate as advanced offense and defense weapons come into use. Given 4 or 5 years, however, it should be possible to develop a more advanced type of system using a large number of specially designed radar "gathering heads." Such a system could overcome the inadequacies of the interim system, result in substantial economies, and have potentialities for further improvement. In its defense study, RAND investigated several possible ways of designing an advanced radar for use in this more advanced system, called Muldar.[4] Some of the findings are discussed here. As noted in Chap. 2, Fig. 2 (page 7), and in Chap. 11, consideration was given to two such systems: a *low-altitude Muldar* and an *all-altitude Muldar.* The first would supplement the present network of big radars, whereas the latter would supplant it.

CHOICE OF A GENERAL DESIGN

Coverage down to 200 ft was used as a design goal, in keeping with the estimates of enemy tactics given in Chap. 5. The line-of-sight restrictions of ground-based radars imply that a relatively close radar spacing is necessary to achieve such coverage. This means that the number of radars needed will be large, and this, in turn, creates a difficult problem in the handling and coordinating of the data obtained from such a system of radar "gathering heads." The success of such a scheme depends greatly on the degree to which false-target data, especially ground clutter, can be eliminated. Therefore, the fundamental problem is to design a radar set which will fit into the system

described and provide a high degree of clutter elimination. The necessary amount of clutter rejection, of course, is a function of the amount of clutter seen by the radar, which, in turn, is dependent on its geographical location. It has been estimated that in order to provide an adequate solution to the problem, the radar must be capable of observing an airborne target in the presence of a clutter signal at least 40 db stronger than the target signal.

Two other desirable characteristics are that the sets yield their data in a form suitable for automatic transmission and that they be as simple and cheap as possible (preferably unmanned) so that the operation of a very large number of sets will be economically feasible.

Further, it has been estimated that the moving-target-indicator (MTI) performance must be obtained simultaneously with the following data and rate requirements: a set of target data (range, azimuth, and elevation) approximately once per 10 sec per target; an accuracy estimated as $\pm \frac{1}{2}$ mile or less in range; and an accuracy of $\pm \frac{1}{2}$ mile or less in azimuth and elevation. (The resultant design, however, is generalized for various data accuracies.)

The influence of vectoring errors on the air battle has shown that, for probable defense-weapon characteristics, these data rates and accuracy specifications are *sufficient* for both aircraft and missile targets.

The following discussion treats relatively short-range radar systems of two generic types: those which gather both low- and high-altitude information (all-altitude Muldar); and those which are required to obtain low-altitude information only (low-altitude Muldar).

The radars examined in consideration of this problem were:

1. Non-space-separated systems (where transmitter and receiver are contiguous) using unmodulated c-w signals. These systems would use
   a. Velocity and angle measurements to compute target location, *or*
   b. Angle measurement to compute target position by triangulation.
2. Space-separated unmodulated c-w radars (where transmitter-to-receiver spacing is roughly equal to the maximum detection range sought). They would use
   a. A single-beam transmitter and receiver, *or*
   b. Multiple-beam transmitter and receiver antennas and multiple receivers.
3. Frequency-modulated c-w range-measuring systems.
4. Pulse systems.
5. Pulse-doppler (keyed c-w) systems.

None of the radar techniques listed above provided a wholly adequate solution to the design problem. Either their theoretical capability or their practicality, or a combination of them, was found wanting. Of the systems considered, however, the pulse-doppler systems are clearly superior to all others in operational capability and in the probability of successful development and field utility.

PULSE-DOPPLER DESIGN

By using time separation between the transmitter and receiver, it is possible to design pulse radar systems that have MTI properties—i.e., that reject ground clutter—while measuring range. Examples that are most familiar involve the use of mercury delay lines attached to ordinary pulsed sets. This, however, is one special case of a large family of possible time-separated radar systems. It is also quite possible to build pulsed systems using lumped-constant delay lines or using multiple range gates with clutter-rejection filters in each range-gated channel. Considerable research and development has been expended to date on the application of single delay lines to pulsed radar sets in order to achieve MTI. This system, however, has theoretical limitations that do not permit the amount of clutter rejection desired for this application. The use of range gates and filters appears to be a promising way of obtaining the desired amount of clutter rejection with only moderate complexity.

This line of approach is desirable for two basic reasons. First, the use of lumped-constant filter techniques allows for the possibility of matching the rejection characteristics of the filter networks to the frequency spectrum of the ground clutter in an optimum and straightforward manner, thereby achieving the necessary high degree of clutter rejection. Secondly, the practical utility and performance of filter techniques in other applications have been well established, and stable high-precision circuitry has been achieved. A brief description of the components and operation of such a system follows.

The transmitter consists of a master-oscillator frequency-multiplier power amplifier which provides radio-frequency power to an antenna through a duplexer assembly. It is keyed in the conventional manner, like a present-day pulse radar system. The receiver has a mixer which is conventional (except that the stable local oscillator is provided from the transmitter chain) and an intermediate-frequency amplifier. A second mixer is located at the output of the i-f strip. At this point a signal, coherent at the intermediate frequency with the signal from the transmitter, is mixed with the received target-echo signal. The signal ouput of such a receiver consists of video signals having

target-velocity information preserved in the form of doppler-frequency shifts. The video output is sampled during each repetition period by successive range gates, and the video present in each gate is then passed into a channel consisting of fixed target-rejection filters, a rectifier, and signal-integration filters.

When a fixed target is present, the frequency spectrum of the output signal from each gate consists of frequency components centered at zero frequency, the repetition frequency, and the harmonics of the repetition frequency. These signal harmonics cover a finite width of spectrum which depends on target-fluctuation characteristics and on the amount of time that the target is illuminated by the radar antenna beam. Moving targets, on the other hand, have a similar spectrum except that each harmonic is frequency-shifted by the doppler effect, the shift being proportional to the target velocity.

If the output of each range gate is passed into a filter with a pass-band located wholly between two repetition-rate harmonics (e.g., between zero frequency and the repetition frequency), then the output will consist of a signal caused solely by moving targets. To extract this simple signal, a third mixer is used which has at its output a simple signal-integration filter.

A target is indicated by the presence of a signal that exceeds a predetermined threshold at the output of the signal-integration filters, and the target range is obtained by knowledge of which range gate responds. Range resolution is provided by the range-gate width, which corresponds to the pulse-width criterion in the usual pulse systems, whereas angular resolution and angular data are obtained in the usual manner from the antenna beamwidth and beam position at the time of a signal response. If the output of each range gate, as described above, is sampled once or twice during the time required for the antenna to move through its half-power width, and if each integration-filter response is adjusted to allow a signal output to persist for this time, then all signals on nonstationary targets are conveniently coded for narrow-band transmission.

In particular, consider such a system having a repetition frequency of 1500 cps (about 60 miles unambiguous range), 25 one-mile range gates, and a 3° beam scanning through 360° in 10 sec. This corresponds to the *low-altitude Muldar* application. There will then be 120 beam positions in a 10-sec period and for each beam position, 25 range samples will need to be taken. The transmission bandwidth required is of the order of 300 cps. In other words, the output of the integration filters may be transmitted over a telephone line, the presence or absence of the center 1500-cps tone indicating a target, and the rate of change of this signal with sampling corresponding to a bandwidth requirement of only about 300 cps. Such a system, therefore, meets the two basic requirements: the

removal of fixed target data and the transmission of the remaining information in a simple and economic manner. Note that for the *all-altitude* design case, approximately 20 additional beam positions (in elevation) must be sampled and transmitted in the same time. Consequently, the bandwidth requirement now becomes about 6000 cps, a figure corresponding to the use of two telephone lines for adequate transmission.

The design restrictions on the described radar system lie almost entirely in the fixed-target rejection characteristics which are attainable, as influenced by the desired performance specifications (range, coverage, information rate, etc.). For certain values of the system design parameters, velocity "dead zones" may occur. That is, if the doppler frequency becomes equal to the repetition frequency or a multiple thereof, the target signal appears to be essentially identical with a fixed-target signal and will be rejected. The width of the spectral components of the fixed-target signal, which must be rejected and hence determine the extent of the velocity dead zones, depends on the fluctuation characteristics of the clutter targets, the resolution and data-gathering rate of the system, and on whether or not rain echoes will be obtained.

For operation at wavelengths shorter than about 20 cm, rain echoes are an important component of the general clutter observed. Their rejection, which is considered essential, may be obtained either by the use of filters in the video response, as indicated above, in which case the dead-zone widths may be considerably influenced by the rainstorm velocity, or by the use of circular polarization in transmission. If the width of the dead zones—i.e., the spectral width of fixed-target frequency components—is small, their existence may be tolerated. On the other hand, if clutter characteristics or the required performance cause relatively wide dead zones, these dead zones may not be tolerated. In this case, a solution is to transmit two carrier frequencies[5] so selected that at least one of them will provide a doppler response in the pass-band of the moving-target detection filter at all times.

PERFORMANCE ESTIMATES AND CONCLUSIONS

The selection of a preferred set of design parameters is largely a matter of judicious compromise, notably among the following quantities: maximum range performance, the fraction of velocity spectrum rejected, wavelength, angular resolution, and scan time. Curves relating these quantities were drawn for both single-frequency and two-frequency operation.[6] From the consideration

[5] Alternatively, different spacings between pulses can be used; this method has advantages in certain applications. See Sec. III, below.

of such sets of curves it is possible to draw two conclusions; these conclusions are stated here for the case in which scan time is of the order of 10 sec and resolution is of the order of 1 mile.

- In the *low-altitude* application, using pulse-doppler techniques, the required performance can be attained most simply by single-frequency operation, together with circular polarization, for rejection of rain echoes. The required 25-mile range can then be met, at any wavelength, with a rejection of only about 3 per cent of the total velocity spectrum.
- In the case of the *all-altitude* operation—when this is achieved by a single scanning beam—single-frequency operation results essentially in a rejection of half the velocity spectrum if 25-mile-range performance is required. Therefore, independent of whether or not rain is to be rejected by polarization or filter techniques, *two-frequency operation is indicated for all-altitude operation.* As a consequence of the two-frequency requirement, rain rejection is most likely to be obtained through rejection filters.

In this circumstance, operation of the scanning-pencil-beam *all-altitude* system to achieve 25-mile-range performance is restricted to wavelengths of the order of 20 cm or longer, *together with* frequency separations of the order of 30 per cent or greater. The antenna sizes required and the high rotation rates necessary at this carrier frequency indicate that a preferred way to achieve the all-altitude operation is to use stacked beams instead of a scanning pencil beam. Through the use of stacked beams, elevation nodding of the antenna is avoided, although some compromise is required between higher antenna rotation rates (up to 20 times that of the simple low-altitude application), the number of receivers employed, and antenna-switching of multiple (up to 20) receiving systems. The preferred all-altitude gathering-head may thus be visualized as a pulse-doppler system using a set of vertical stacked beams, each acting like a low-altitude Muldar unit; in order to avoid undue complexity, an MTI receiving system would be used on only a few of the lower beams and a non-MTI receiver would be used on the greater number of upper beams. The receivers would be switched to successive antenna beams for successive antenna rotations, the entire ensemble being covered in the allowed scan time.

All the performance figures presented depend somewhat on the complexity of the design of the rejection filter. The values given above correspond to a filter construction using approximately 25 reactive elements per range gate.

This figure is a measure of the complexity of the system.

It was concluded that a radar system having the performance characteristics required for the *low-altitude* role can be developed if the techniques described above are employed. It was also concluded that if the pulse-doppler and multiple-beam antenna techniques are exploited to their fullest capabilities, the desired performance of the *all-altitude* radar can be achieved. The development and operation of this latter system, however, will require a high degree of technical competence in design, production, and use.

III. AMTI for Interceptors

In the discussion of low-altitude data-gathering techniques, it was mentioned that interceptors could have some low-altitude effectiveness without attempting to remove ground clutter with airborne moving target indication (AMTI). Although present evidence indicates that this is true, especially at altitudes of about 1000 ft or more, the time required for interception is longer and the probability of interception is less than at higher altitudes, where ground clutter is not a problem. RAND's Air Defense Study showed that it would be desirable to improve the low-altitude interception capability of interceptors.

It has already been pointed out that daylight interceptions can often be made visually. At night, since a bomber would probably need to use a navigation radar, passive detection means might be a considerable aid to low-altitude interception. In addition, infrared shows considerable promise for low-altitude interception at night. Both of these equipments would be light in weight, and they could probably be carried in addition to AI equipment.

These techniques, however, are not entirely satisfactory. Passive detection could probably be used only at night and could be nullified by the bomber's turning off his radar during the interception phase. Infrared has only limited range and does not have all-weather capability. These should therefore probably be considered to be auxiliary techniques, and it would be very desirable to develop an AMTI system for the interceptor's AI radar that would reduce the ground clutter and obtain the long ranges and good probability of detection that can be achieved with modern AI equipment at high altitude.

CLUTTER SPECTRA AND REJECTION CHARACTERISTICS

As a consequence of the speed of the interceptor itself, and the fact that the beamwidth of the antenna is broad enough to see ground echoes of various radial velocities, the doppler signals from the ground clutter have a large

velocity spread. (It is usually convenient to refer to frequencies in terms of the equivalent radial velocities.) This spread is such that conventional single-delay-line MTI techniques combined with usual AI parameters cannot reject very much of the clutter because the rejection characteristic is very narrow, whereas the ground-clutter spectrum is fairly broad.

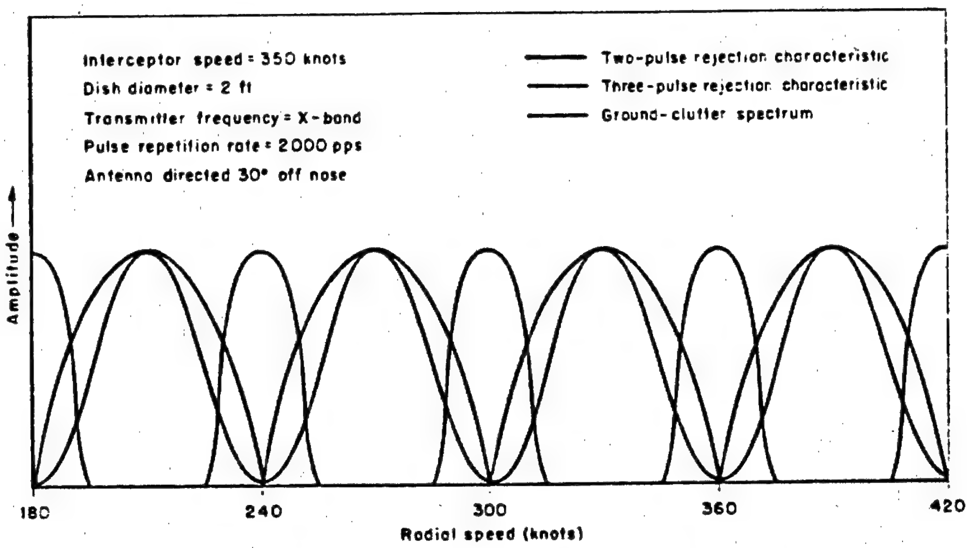


Fig. 97—Comparison of two- and three-pulse cancellation systems, where pulse repetition rate equals 2000 pps

These spectra are illustrated in Fig. 97 for a particular case. The clutter spectrum shown is approximately that which would be obtained by using a radar with noncoherent[7] AMTI having conventional parameters, if it were viewing a uniformly scattering earth at an angle of 30° from the direction of flight when the interceptor was going at 350 knots. The clutter spectrum shown is caused only by the beam shape of the antenna and the motion of the interceptor. That is, the width of the spectrum is caused by different pieces of ground clutter being viewed from different angles by the antenna. This causes each piece of clutter to have a different radial velocity with respect to the radar, but because of the antenna shape, each velocity component is received with different antenna gain. The beam shape, therefore, is important in determining the spectrum spread; the beam shape is, of course, determined by the

[7] By a noncoherent system is meant one in which the returned signal is mixed with the ground clutter rather than with a local oscillator having a fixed phase relationship with the transmitter. In such a system there is no coherent oscillator.

antenna illumination. Actually, the illumination function does not seriously affect the amount of rejection obtainable when the over-all rejection is of the order of 20 to 40 db. For the illustrations used here, a triangular illumination has been assumed. The scanning of the antenna would tend to spread the spectrum further, but this can be minimized by requiring less volume to be searched at low altitude. If the antenna were pointed 90° off the nose, the spread would be about doubled. If it were pointed dead ahead, the spread would be very much narrower.

Figure 97 also shows a rejection characteristic obtainable by using a two-pulse-comparison MTI system with typical AI parameters. (The conventional single-delay-line MTI, of the type used in present ground radars, uses a two-pulse comparison.) In this system each returned pulse is subtracted from the succeeding pulse (at the same range). It is seen that very little of the clutter spectrum can be rejected because the spctrum is comparatively broad, whereas the rejection characteristic of the MTI is narrow. It is, of course, possible to compare more than two pulses. That is, a system could be built which would add or subtract, with various weighting factors, three or more pulses; it would then be possible to obtain a variety of MTI rejection characteristics. In Fig. 97 the red curve shows the broadest rejection characteristic obtainable with three-pulse comparison. Even so, the rejection is not quite adequate and there are many broad rejection bands or dead zones[6] in the desired velocity band.

ALTERING THE SYSTEM PARAMETERS

The most straightforward way to obtain better MTI rejection is to compromise the performance by changing the AI radar parameters and then to reconsider the various MTI pulse-comparison techniques mentioned above. The clutter-to-target signal ratio can be decreased somewhat by *shortening the pulse width* until it becomes comparable in space with the length of the target. A 0.25-to-0.1-μsec pulse is probably narrow enough. The gain that can be achieved in this way, therefore, is limited, and in any event the ratio depends quite strongly on the type of terrain.

Varying the designed transmitter frequency does not at first appear to produce much improvement, assuming that the antenna size is held constant. A decrease in frequency, although it produces an increase in the velocity separa-

[6] The dead zones are regions occurring at multiples of the repetition frequency where, because of the repetition of the pulses, both the clutter spectrum and the rejection nulls are repeated.

tion of dead zones, also increases the clutter spectrum by widening the beam width; hence, the clutter rejection tends to remain constant. There are, however, some possible reasons for decreasing the transmitter frequency which will be mentioned later.

Increasing the pulse repetition rate, however, gives promise of making AMTI more feasible. For instance, if an unambiguous range of 15 nautical miles is chosen, the repetition rate can be about 6000 pps. With this repetition rate, and for the same conditions of interceptor speed and antenna angle, the ground-clutter spectrum appears more like that shown in Fig. 98.

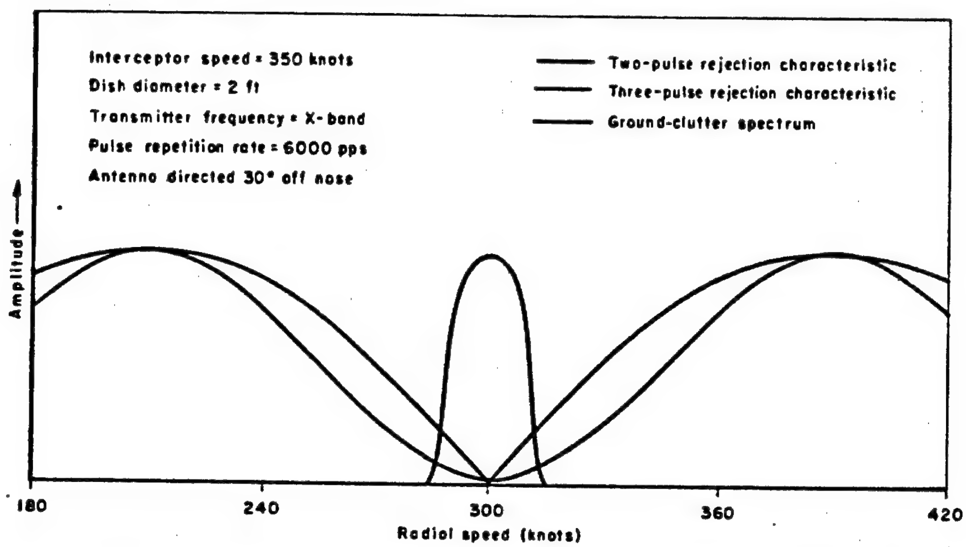


Fig. 98—Comparison of two- and three-pulse cancellation systems, where pulse repetition rate equals 6000 pps

From this it is seen that the rejection is more complete over a wider band and that there are fewer dead zones in the useful velocity region. Figure 99 shows several rejection characteristics obtainable with two- and three-pulse comparison, as well as the ground-clutter spectrum for the case discussed above. This figure, and the two following figures, have abscissas in terms of speed differences relative to the radial ground speed. The rejection obtainable with two-pulse comparison in this case is about 22 db, whereas that obtainable by using the steepest three-pulse comparison is nearly 38 db. (These numbers were obtained by integration over the whole clutter spectrum.) This larger rejection is obtained at the expense of less pass-band, but the use of three or more pulses permits the removal of dead zones from the pass-band, as explained

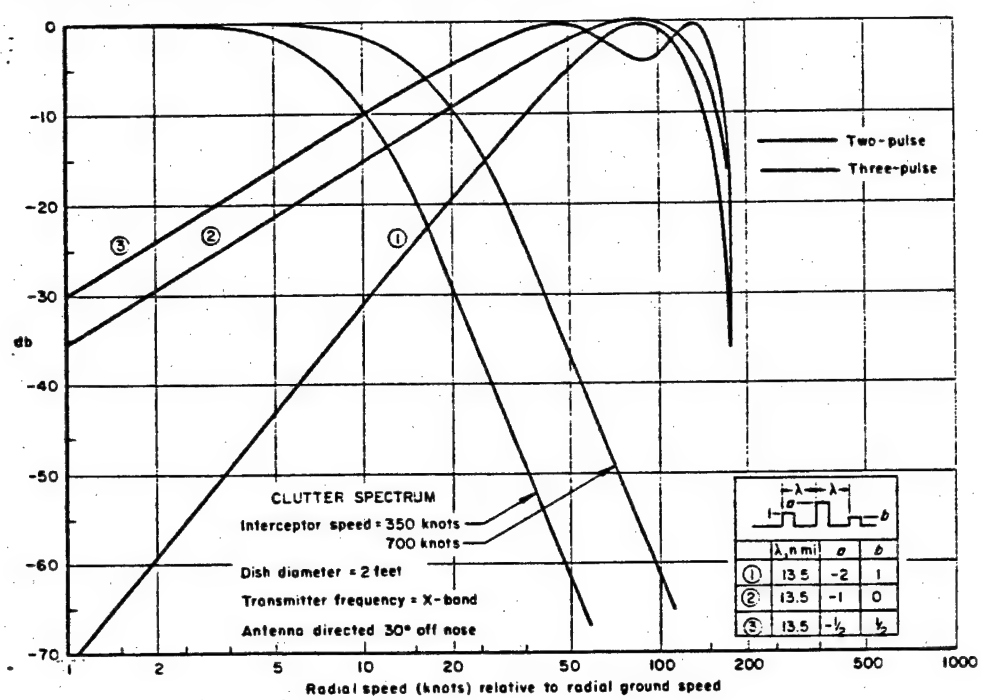


Fig. 99—MTI rejection curves, showing various pass characteristics for two- or three-pulse comparison—single pulse spacing

below. Figure 100 shows a few possible rejection characteristics obtainable with four-pulse comparison. Here it is seen that large rejections are theoretically possible over a wide velocity band.

REMOVAL OF DEAD ZONES

By using different spacings between the pulses in alternate pairs, it is possible to decrease greatly the dead zones in the pass-band. Alternatively, two transmitter frequencies could be used. For AMTI, the varied spacing between pulses is probably better and easier to use. Figure 101 shows two possible rejection characteristics which can be obtained by using three-pulse comparison and two different pulse spacings. It is seen that the same rejection characteristic can be maintained with near zero relative velocity as with uniform spacing, but the dead zones can be reduced or removed. In curve (1) of Fig. 101, essentially six dead zones have been removed by the particular spacing chosen, rendering a dead-zone-free pass-band of over 1000 knots. This may be more than is necessary for tactical use. A better pass-band characteristic could be obtained

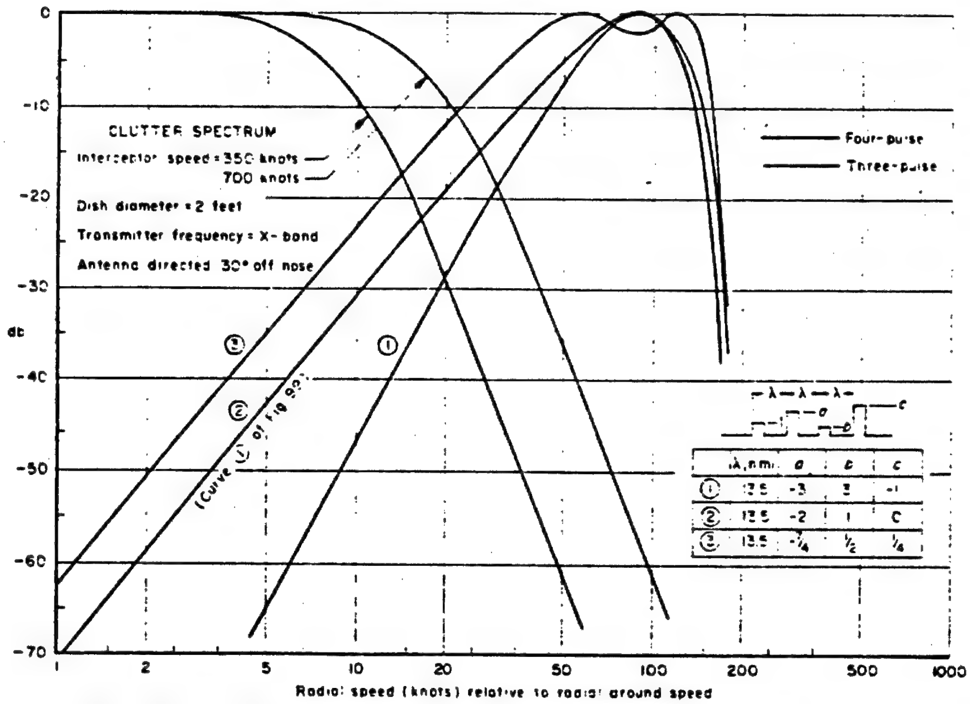


Fig. 100—MTI rejection curves, showing various pass characteristics for three- or four-pulse comparison—single pulse spacing

by removing fewer dead zones, as shown in curve (2) of Fig. 101. Here the dead-zone-free region is about 600 knots. Of course rejection curves of many possible shapes are obtainable—Fig. 101 is merely illustrative. It is possible to consider comparison in groups and then, after rectification or integration, to compare these groups. Many different rejection-curve shapes can then be obtained.[9] It is seen, however, that a rather desirable rejection characteristic can be obtained by means of the simple comparison method shown in Fig. 101, which uses two pulse periods and three-pulse comparison. The clutter rejection obtainable with a characteristic such as that of curve (2) of Fig. 101 is better than 40 db for the case considered, and the desired pass-band has no dead zones greater than about 10 db down. If the interceptor velocity were doubled, this would essentially double the width of the velocity spectrum of the ground clutter. The clutter rejection would then be reduced to about 25 db, but this might be sufficient, since interceptions can sometimes be made now with no AMTI at all.

Another way to remove the dead zones from the desired doppler band is to

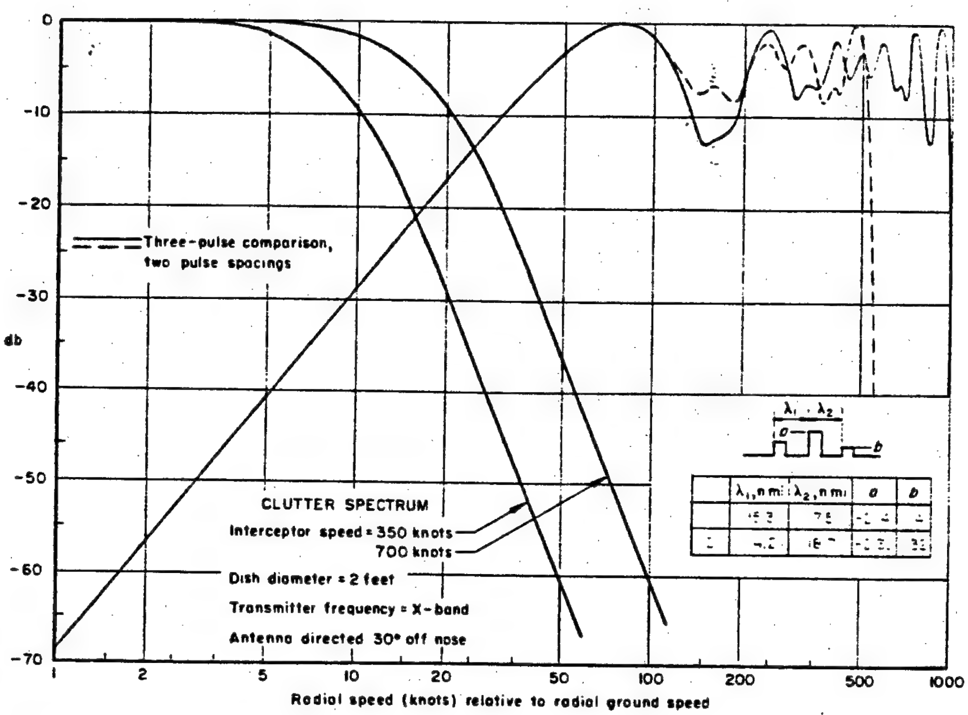
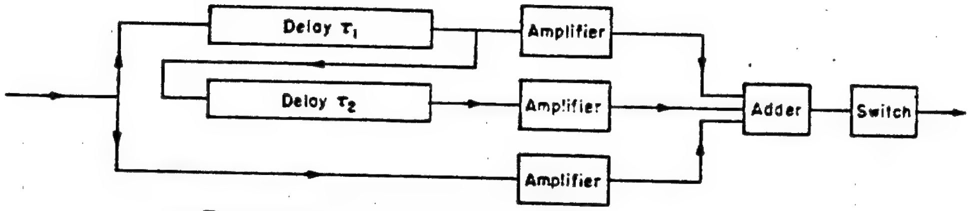


Fig. 101—MTI rejection characteristics, showing suppression of velocity dead zones

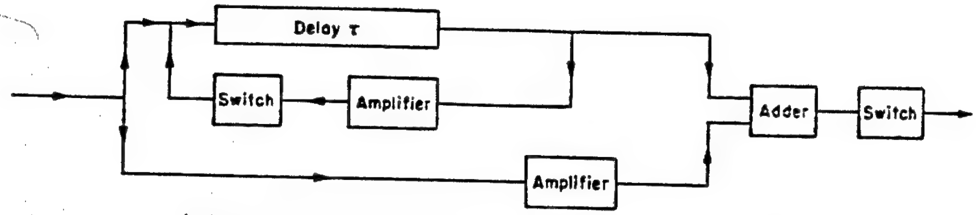
go to a lower transmitter frequency. This, to a first approximation, would merely change the velocity scale in Fig. 98, so that at C-band the dead zones would be 360 knots apart; at S-band they would be about 540 knots apart. Lowered transmitter frequency would have the advantage of requiring less rapid search to cover a given volume in a given time, and hence would reduce the scanning noise, but it would sacrifice angular resolution.

WAYS OF OBTAINING MULTIPLE-PULSE COMPARISON

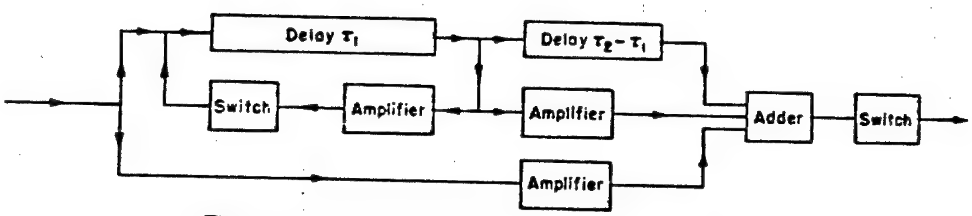
Multiple-pulse comparisons can be made in a number of different ways; the choice of which is best is dependent on which circuit elements are most reliable or easiest to maintain. For instance, a separate delay line can be used for the time period between each pulse to be compared, as shown in Fig. 102*a*. It should be remembered that with a fast repetition rate the length of the delay line can be quite small. It is also possible to use multiple channels through one delay line, or to use feedback and switching through the same



a. Three-pulse comparison system using two delay lines for equal or unequal pulse spacings



b. Three-pulse comparison system using one delay line, with interrupted feedback loop, for equal pulse spacings



c. Three-pulse comparison system using two delay lines, with interrupted feedback loop, for unequal pulse spacings

Fig. 102—Examples of three-pulse-comparison circuits

channel of one delay line, as shown in Figs. 102*b* and 102*c*. If this is done, some pulses pass through the delay line twice, others once, and others are compared directly for three-pulse comparison. When different spacing is used, an additional small delay line is necessary to get all the pulses together at one time for comparison, as shown in Fig. 102*c*, and the output must be gated-on only during the proper period.

It is also possible, with the high repetition rate, to consider the use of multiple range gates followed by filters instead of delay lines, as was discussed previously in connection with the Muldar system. This technique would give results similar to those obtainable with delay lines. It is not feasible, however, to use narrow pulses with this scheme, as the number of gates would then become prohibitive. For the AMTI case, it is probable that multiple delay lines, or delay lines with switching and feedback, are more feasible because of the

desired resolution and because very large rejection is not required. For the tracking phase, however, in which a range gate is normally used, velocity gating by means of filters would probably be appropriate.

OTHER CONSIDERATIONS

There are, of course, many more considerations other than the actual MTI filter characteristic. One major consideration is the return from clutter farther out than the unambiguous range of the system. If a noncoherent magnetron transmitter is used, in which the phase is not correlated from pulse to pulse, then such returns will be uncorrelated and will not be rejected by the MTI filter. If sensitivity time control[10] is used, the worst range will be close to 30 miles for a 15-mile unambiguous range. The return of this type will be down by about 10 db (compared with the corresponding first-time-around clutter echoes). If the interceptor flies higher than the target, this return will be suppressed further by the antenna-pattern selectivity. Two miles altitude gives about 20 db additional rejection. The rejection of these second-time-around echoes could be reduced even more by increasing the unambiguous range slightly, say, to 20 miles, and blanking the return from about 15 to 20 miles, while using sensitivity time control from 0 to 15 miles range. This adds about 5 db of rejection at the worst range. A better solution would be to use a coherent transmitter, such as one with a Klystron amplifier, so that all returns from second-time-around echoes would be correlated. If this were done, it would be better for the interceptor to fly low, which would cause first- and second-time-around echoes to have more nearly the same spectrum.

The ground-clutter spectra considered in the above discussion did not include the spread caused by antenna scan. The clutter spread shown was due only to interceptor speed and antenna-beam shape. If the antenna were scanned rapidly to cover a large volume of space, as is the case at high altitude, the clutter spectra would be spread further than those shown because of the antenna motion. When searching at low altitude, this could be avoided by greatly reducing the volume scanned so that the scanning speed would be slower. If good vectoring data were obtained, this would be quite feasible, because the region in which MTI is necessary is under about 5000 ft. If a target were known to be in this region, the antenna would need to be scanned over only a limited elevation angle; if the low-altitude data were good to within about 1 mile, it

[10] Sensitivity time control is a way of varying the receiver gain, as a function of the range of received echoes, in such a way as to suppress the effect of the radar range equation (within the available amplification limits).

might be possible to limit the azimuth scan also, with only moderate sacrifice of tactical effectiveness.

Another consideration in any MTI scheme is transmitter stability. To obtain good AMTI rejection with multiple-pulse comparison, it is necessary to have good frequency and amplitude stability over several pulse periods. The requirements are less severe for a noncoherent system than for one using a coho (coherent oscillator), but if large rejection is desired, this stability can be the limiting factor. In some cases this may lead to a choice of a transmitter consisting of an amplifier fed by a crystal-controlled frequency source.

CONCLUSIONS REGARDING AMTI DESIGN TRENDS

The preferred AMTI system for the near future appears to be an X-band radar having about 15 miles of unambiguous range, with two different pulse spacings and three-pulse comparison. Some form of velocity filtering should also be used in the tracking phase. At first, the transmitter could probably use a magnetron; eventually, a crystal-controlled transmitter might be desirable.

If the volume to be searched is limited so as to reduce scanning noise, and if the search angles are not too large, this system could have good clutter rejection with no dead zones in the desired doppler band when flown at speeds between 350 and 700 knots at low altitude. This AMTI equipment would normally be turned off during operations at medium and high altitudes.

IV. Low-Altitude Effectiveness for the Bomarc-Type Missile

It is possible for an area-defense missile such as Bomarc to be made to have low-altitude capability. To accomplish this, it must have a seeker which rejects ground clutter and which can lock on and track low-flying targets; it also requires a ground radar system capable of providing adequate low-altitude target data for mid-course guidance purposes. It appears to be much more difficult to obtain low-altitude effectiveness with an area-defense missile than with either an interceptor or a local-defense missile. In the case of the interceptor, low-altitude control data are required, but because of the presence of an operator in the interceptor, the data need not be very precise, and some effectiveness can be achieved without requiring clutter rejection in the AI equipment. In addition, the time requirements for search and lock-on are not severe for the interceptor. Most local-defense missiles have the advantage of not requiring good low-altitude coverage suitable for control over a wide area. They require only early-warning-type data for alerting and for crude directing.

However, there are definite advantages to be gained by providing an area-defense missile with low-altitude capability. For instance, the greater protected radius permits one-half to one-fourth as many missiles to be used as are needed for local defenses. Furthermore, an area-defense missile, the Bomarc, is already under development. The following paragraphs suggest ways in which a Bomarc-type missile might be made to work at low altitudes.

If the interim low-altitude-radar network (described at the beginning of this chapter) is used for interceptors, it may be possible to feed the low-altitude data into control stations and obtain data for missile control. Such data will not be entirely free from ground clutter. This may be suitable for manual interceptor control but may not be good enough for automatic track-while-scan computers in a Bomarc-type system. Good correlation would also be required between high-altitude and low-altitude data in an automatic system. The low-altitude interim radar system proposed in this chapter has a variable delay in data presentation of up to 10 sec. Although this does not affect interceptor control, it may be significant in the control of a fast missile.

In spite of these difficulties, it might still be possible to obtain limited low-altitude effectiveness with missiles by using interim radar techniques and manual control similar to those used for the interceptor. Ideally, however, an area-defense missile would require a Muldar system which would employ radars having excellent MTI properties corresponding to those discussed earlier; data from many Muldar gathering heads would then have to be correlated for each area-defense-missile station.

Having the low-altitude control data, it is then necessary to design a missile seeker that can acquire and track low-flying targets. Some effectiveness may be achieved through the use of a conventional seeker by programming the missile to fly a course that would cause the missile to approach the bomber from directly overhead. Then, by searching out in range, the tracking range gate could acquire the target before the gate intercepted the ground. This, however, is not a very satisfactory solution because it depends too critically on the low-altitude data for success. Further, if the gate missed the target, there would be a high probability that it would lock on the ground and fail to search again for the target. In addition, the tactics of the missile are severely limited when this type of approach is required.

A more attractive possibility is to develop an active seeker using coherent pulse-doppler techniques with a high repetition rate and using both range and velocity tracking, similar to that described below for the local-defense missile. Although the techniques could be similar for this seeker and the local-defense-

missile seeker, the problems are more difficult for the area-defense-missile seeker. The fact that the seeker is active means that duplexing is necessary and that the recovery time of the TR box must be considered. The high closing speed during acquisition allows less time for acquisition and places severe constraints on the seeker, since it must lock on the target in range, velocity, and angle in a short time. Furthermore, since the missile is in motion and may attack the target over a wide range of angles, it becomes very difficult to select the velocity range that contains the target and not ground clutter.

The difficulties likely to be encountered in making the long chain of required equipment function properly are considered to be severe. It is felt, therefore, that effective low-altitude defense may be obtained earlier by other means. Nevertheless, RAND feels that seeker and data-gathering developments for area-defense missiles are important and suggests that these should be continued along the lines indicated in this chapter.

V. Guidance for the Local-Defense Semi-Active Missile[11]

The requirements which a future local-defense guided-missile system must satisfy, to provide an adequate level of defense strength for a reasonable cost, may be appreciated by reviewing the salient factors that have been emphasized in the analyses presented in the previous pages of this report. These are, in general:

- Low-altitude defense by guns or rockets is difficult and costly to obtain. Hence, a missile guidance system that could effect kills at low altitude more cheaply than other low-altitude weapons (and at the same time add to the killing power at high and medium altitudes), would reduce the cost of defense considerably.[12]
- Much of the expense of conventional low-altitude weapons can be attributed to the number of operating personnel required. This number is quite large because of the very short range of these weapons and the resulting large number of weapon installations required. A missile having sufficient range to defend a point or a small area target having a small number of missile stations (e.g., two or three) would materially reduce the number of men required, and hence the cost of the system.

[11] The missile itself is described in Chap. 9.

[12] Savings in cost, as mentioned here and in the following paragraphs, should be interpreted in relation to the possibility of inadequate total defense strength with probable budgets, as pointed out in Chap. 2.

- The over-all defense cost could also be reduced considerably if future and more advanced threats could be handled by the same defense weapon. Conventional low-altitude weapons can be rendered very ineffective by an increase in the speed of the attacking bombers or by the use of short-range offense missiles having both higher speed and smaller cross section. Consequently, a missile guidance system that could protect against threats at all altitudes and kill small high-speed targets would result in a large saving in defense cost.
- Another cost saving (compared with presently proposed missile guidance systems) could be effected if less money went into ground equipment. A given locality in an atomic war might experience only one or two attacks in which fairly large numbers of aircraft attacked simultaneously. To combat such a threat, a system having a tracking radar for each target would require one tracking radar for each two or three missiles fired; consequently, the number of tracking radars might be large. A substantial saving in defense cost would result from the use of a system needing less ground equipment per missile fired.
- The fact that men and overhead are by far the largest items in the cost of a weapon system should certainly be considered in designing a system. The initial cost of the weapon, when amortized over a 4-year life expectancy, was usually small compared with the cost of manning and maintaining the equipment. Hence, higher-cost equipments that will increase kills without greatly increasing personnel requirements may significantly increase the kill potential per dollar.

Of all of these objectives, the most important (and at the same time the most difficult to achieve) is the low-altitude capability. Once this is achieved, the guidance can be made to work at high altitude or against advanced threats with relatively little additional expense. Low-altitude capability should therefore be the dominant criterion in choosing a guidance system.

For low-altitude missile guidance, ground clutter must be almost completely removed. Otherwise the probability that the missile will track on ground clutter is intolerably high. To achieve ground-clutter elimination, some form of velocity discrimination is necessary.

A large variety of guidance systems were examined for the generalized missile to see which system came closest to satisfying the important considerations listed. The best choice among the possibilities is considered to be a pulse-doppler system using a sufficiently high repetition rate to ensure that

the pulse-repetition frequencies are not in the doppler spectrum. This system shows promise of obtaining very great rejection of ground-target signals while maintaining good range discrimination. The one penalty that results is that range is ambiguous as a consequence of the high repetition rate. Since absolute range, although desirable, is not necessary for homing, this penalty is not too drastic.

To reduce the cost of ground equipment—and hence the cost of the system—while allowing rapid rate of fire, a semi-active system with homing-all-the-way guidance and wide-angle illumination from the ground is preferred. Each missile could then take off as soon as it found a target, and the targets need not be tracked by individual ground radars.

SYSTEM OPERATION

For purposes of illustration, the kind of operation visualized against bombers will be described first and the additions necessary to cope with a more advanced threat will be discussed later.

The missile considered is a semi-active homing-all-the-way missile having no mid-course guidance—i.e., it begins to home from the ground. The target is illuminated by a ground-based transmitter having a wide antenna pattern, so that accurate pointing of this antenna is unnecessary. The missile seeker also has a wide-beam antenna and can therefore find the target with only crude aiming in elevation and azimuth. Each missile acquiring a target tracks it in range by using a range gate, in velocity by using a velocity gate, and in angle by means of conical scan or monopulse tracking. The velocity and range gates allow discrimination against ground clutter and against ground reflections, thus permitting homing on low-flying targets. In addition, they promise to eliminate chaff echo, since chaff is behind the target aircraft and has a different velocity spectrum. They also provide a good means for distributing the missiles over a large number of bombers so that the missiles-per-bomber ratio is uniform throughout the attacking formation. Through the use of velocity and range gates, a target selectivity in angle is provided which is nearly equivalent to using a narrow beam, so that the missiles are not easily confused by targets which are close together; the gates accomplish this without actually requiring a narrow beam, which would necessitate angular search. Once the missile antenna is able to track a particular target in spite of ground clutter and ground reflections, the missile can be made to home on the target by using the conical scan to measure angle and proportional navigation to obtain a hit or near miss. The missile fuze can be triggered either by a rate of change of angle or by

range sensing, the latter probably being preferable. This fuze would use the tracking gate to measure range and the rate of change of signal strength to remove range ambiguity. The use of VT fuzes is possible, but they may be less desirable because of jamming or ground clutter.

TACTICAL USE OF THE WEAPON

Basically, the proposed missile system is visualized as working in the following manner: At a particular missile station, there would be a fairly wide-angle illuminator and a number of missiles mounted in a vertical position, being sufficiently high (20 ft or more) and free from obstructions so that targets could be detected at low altitude between 10 and 20 miles away. When a bomber or a group of bombers approached, the illuminator would be turned on from early-warning data and the missile antennas would be pointed to within about 20° to 30° of the proper azimuth of the bombers. When the missiles had locked on the bombers and the bombers had approached within range of the missiles, as indicated by a surveillance radar, the missiles would take off and climb to about 2 miles altitude in a bending, programmed trajectory. At that time the homing guidance would take over and direct the missiles into a collision course, using proportional navigation. Thus, the missiles would fly down on low-flying bombers or up toward high-flying aircraft or missiles.

As a result of considerations of target system geography, enemy threat, cost, and technical problems, the interim local-defense missile was designed to have a range of about 20 nautical miles at low altitude and a maximum velocity of about 2000 fps. This assumed a need to defend against a threat in which bombers might carry subsonic missiles which, if launched just before the bomber was about to be hit, could be attacked by another local-defense missile and be met about 5 miles from the target. Thus, each missile station could defend approximately a 5-mile radius. If the targets were bombers at medium altitude, it would be possible to fire two salvos at them. In the case of attack by a high-altitude bomber, a missile might be launched at the bomb itself if the bomber were not hit.

DESCRIPTION OF SEMI-ACTIVE GUIDANCE SYSTEM

The illuminator on the ground is to be fed by a crystal-controlled oscillator and amplifier so that the frequency will be stable and can be used to obtain coherent doppler signals. It is to transmit short pulses with a high repetition rate. The short pulse width will provide good discrimination in range, which

is useful in selecting bombers and, what is more important, is helpful in eliminating the ground reflection of a low-altitude bomber. The high repetition rate, which will allow unambiguous velocity tracking, will cause range ambiguity of the order of 1 mile. That is, the echo from every target will appear approximately every mile for a repetition rate of 100 kc, for example, so that all targets that can be seen will be seen within a single mile section, and it will not be possible to tell in which mile a target is traveling. This condition is not necessarily a disadvantage, however, since the missile does not need to know the actual range of a target in order to track it and home on it. There is also the advantage that it allows the velocity to be tracked without ambiguity; consequently, there is tracking in range and unambiguous tracking in velocity.

Figure 103 shows the difference in the frequency spectra of signals received at the missile when it is stationary and when it is in motion toward a target. When the missile is on the ground, it receives the transmitter spectrum directly, in addition to reflections from the ground, which produce a small frequency spread around each harmonic. It also receives returns from moving targets, the shift in frequency being proportional to their velocity. One such target is shown in Fig. 103. Such moving-target spectra can easily be seen when the missile is standing still, and a tracking filter can be placed on the target signal.

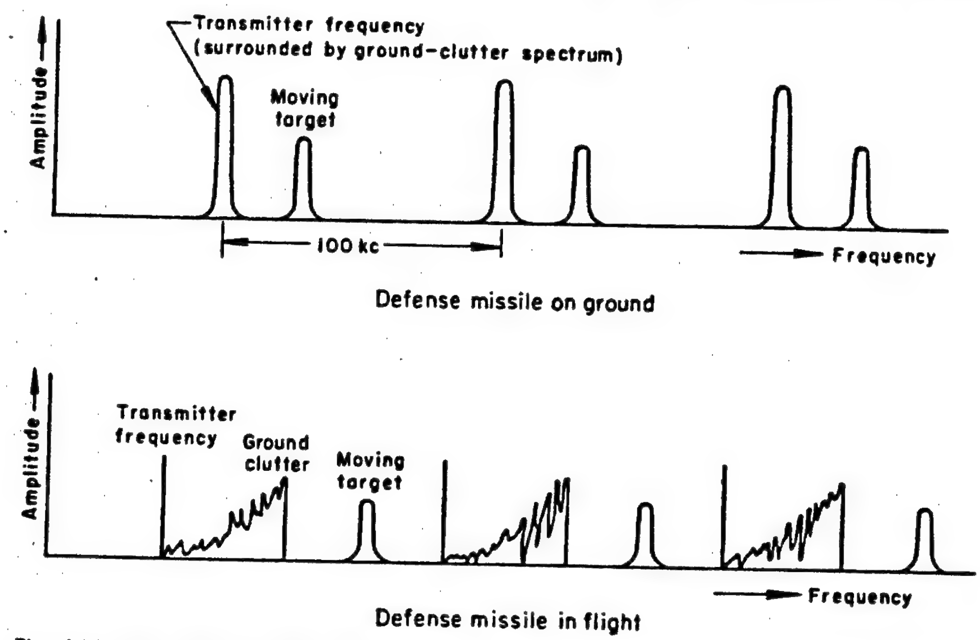


Fig. 103—Frequency spectra for stationary and moving missiles, showing moving targets and ground clutter

As the missile takes off and acquires velocity, the transmitter frequency, as received by the missile, is decreased because the missile is moving away from the transmitter. Similarly, the return from ground clutter near the launcher is decreased in frequency. On the other hand, ground-clutter return in front of the missile is increased in frequency, since the missile is moving toward such clutter. Hence, the ground-clutter spectrum is spread out over a doppler-frequency band which, expressed in miles per hour, is almost as wide as the missile-velocity spectrum. When the target is coming toward the transmitter and missile, its velocity is added to the missile velocity, and the target is always at a higher frequency than the ground clutter. If a velocity gate is placed on the moving target and is made to track it, the output of the gate will be free from ground clutter and the gate will be at a frequency higher than the ground-clutter frequencies by the same amount as when the missile is standing still.[13] It is possible, then, for the missile to place a tracking range gate on a particular target and to select at the output of that gate the frequency of the target by placing a narrow tracking filter around that frequency.

LOW-ALTITUDE AIRCRAFT

If the illuminator and the missile are at an altitude of about 20 ft or more, and if there are no mountains or other obstructions in the way, the missile can lock on targets which are between 15 and 20 miles away and which have an altitude of 200 ft or more. Moreover, because of the velocity gate, a missile can select a target and adequately eliminate ground clutter.

When the low-altitude target is viewed at grazing incidence, it appears essentially at one range with no reflection from the ground. If the missile is programmed to go up while tracking the target, the image of the target appears and moves away from the target. The actual target, however, is always the nearer of the two echoes, so that if the pulse is narrow (e.g., 1 μsec) and the range gate is made to track the leading edge of the echo pulse, then the gate will track the target and not its image.

BOMBER DISCRIMINATION

The use of both a velocity gate and a range gate facilitates discrimination of individual bombers in a formation. Even if the bombers jockey back and forth, there is a fairly small chance of confusing both gates.

[13] There is also good reason to believe that, if the target were to turn around in a feinting maneuver after the missile was locked on, the combination of range and velocity tracking gates could continue to follow the target through ground clutter with better than a 50 per cent probability.

Considering the velocity gate, Fig. 104 shows how a second bomber would have to control its speed in order to be in the same velocity gate as a given bomber. Here the two bombers are assumed to be flying parallel courses, separated by an angle θ, as viewed from the missile. The sum of the velocities of $v_0 + v_1$, and Δv is the additional speed the missile and of the first bomber is required of the second bomber in order to be in the same gate. Figure 104 is drawn for the sum of the two velocities equal either to 2000 knots or to 3000 knots. The faster the speed of closure, the more sensitive the discrimination.

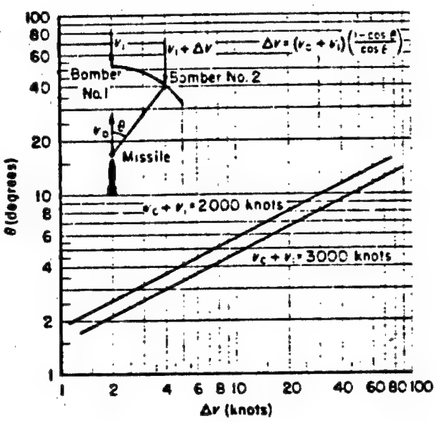


Fig. 104—Offset bombers—increment in velocity for equal closing velocity

By using the 2000-knot closing speed plotted in Fig. 104 for a bomber on the same arc as the first bomber and 5.6° away, the velocity difference required is seen to be 10 knots; 10° away it is 31 knots; and 15° away it is about 70 knots. If the filter is about 20 knots wide, then a bomber 15° away must have an additional velocity of 70 ± 10 knots and be within 50 ft (the range resolution) of the correct range position, since the correct place and speed are changing rapidlyw ith time as the oncoming missile changes its position and direction. From the sketch in Fig. 104, it can also be seen that if the missile approaches the bomber from a slight offset angle, the velocity difference is increased. Hence, it is believed that the missile can track the bombers in formation without confusion, and more successfully than most other missile guidance systems considered. The velocity gate is equivalent, in a sense, to angular discrimination that can be obtained by using a narrow beam, but the equivalence is not complete.

PROGRAMMING THE MISSILES OVER THE TARGETS

Assignment of missiles to certain enemy targets should be as uniform and as automatic as possible. A group of missiles sited close together could all have their antennas pointed in the direction (indicated by early-warning or surveillance radar data) from which enemy aircraft were approaching. When the aircraft were detected by the radar, at a range of 15 to 20 miles, signals would be visible in the video of each missile. During this search period, the narrow

velocity filter would be switched out and a wider filter used. This wide filter would pass doppler frequencies covering a sufficient velocity range to be sure to detect enemy bombers, but it would still eliminate ground clutter and slowly moving targets (automobiles, etc.). The enemy targets, which would be visible on an A-scope if it were attached to the missile-seeker output, would move through the 1-mile range base in such a manner that all visible targets would move past a given point on the range base in the time it would take an individual target to travel 1 mile.

It would be possible to arrange the first missile so that it would begin to track when a target entered its gate, and at the same time it would turn on the next missile, and so on down the line. By turning on the gates of the missiles in this sequential fashion, all missiles could be assigned within the time it would take one target to fly the unambiguous range, and each could be assigned to a different target, assuming fewer missiles than targets, until all the missiles were assigned. An alternative method would be to distribute the gates of the missiles along the 1-mile range base and turn them on simultaneously for a short length of time. With either technique, the missiles could be assigned essentially uniformly to the targets.

SYSTEM DESIGN

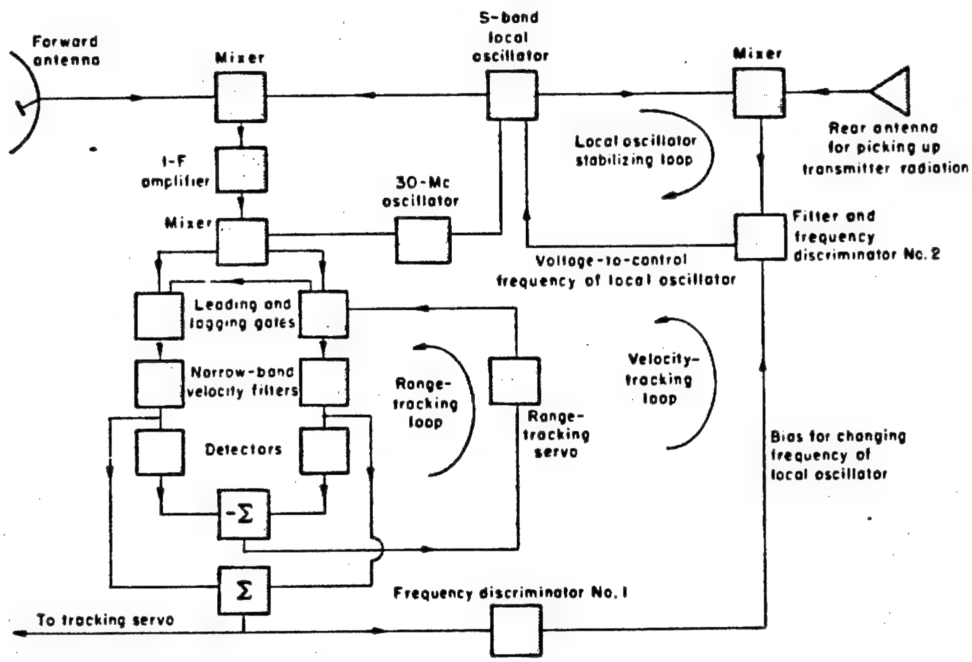
A discussion of the compromises and other considerations which lead to a choice of values for the seeker design parameters is given in RM-629.[14] One fairly acceptable set of values would be the following:

Seeker antenna diameter	2 ft
Transmitter wavelength	10 cm
Pulse width	0.1 μsec
Pulse repetition rate	24 kc
Unambiguous range	3.6 miles
Transmitter average power	100 kw
Illuminator coverage	180° × 40°

The power suggested is not considered to be technically impossible to achieve if Klystron amplifiers are used. It is estimated that it would be feasible to make sealed-off tubes having 50-kw average output and almost the desired repetition rate and pulse widths. The tubes could be used in parallel, or possibly

more powerful tubes could be designed, or compromises could be made in the volume illuminated.

The principal problems in the designing of seeker circuits are (1) to make them sufficiently stable under shock and vibration to permit continuous tracking and (2) to reduce the effects of local-oscillator noise. The complexity, however, need not be noticeably greater than that of presently designed semi-active guidance systems. Figure 105 presents a block diagram of one possible way that the tracking and local-oscillator stabilization might be achieved. The rear antenna is used to pick up the transmitted frequency and side bands. One of these side bands is mixed with one side band of the modulated local oscillator. The difference is fed back through a filter (of width equal to the repetition rate) and then through frequency discriminator No. 2 to control the local-oscillator frequency. The velocity-tracking loop can be completed as shown in Fig. 105 by supplying a bias to the output of frequency discriminator No. 2 to change the local-oscillator frequency by the amount necessary for velocity tracking. Range tracking is accomplished by means of a split gate in the con-



This schematic diagram shows the velocity- and range-tracking loops and a possible way of obtaining a stable local-oscillator frequency.

Fig. 105—Semi-active local-defense missile guidance

ventional manner. This is one possible way of realizing the various tracking loops and is not necessarily the preferred way.

Another channel, either in the missile or on the ground, must be used for search. This channel (not shown in Fig. 105) would contain amplifiers of wider bandwidth than those in the range-tracking circuits, so that search would be done in range first and then in velocity.

ADVANCED GENERALIZED LOCAL-DEFENSE MISSILE

For the advanced missile system, where the velocities are higher and the required range for acquisition is greater, essentially the same guidance system can be used by increasing the illuminator power and the missile speed and by changing the circuitry to handle the greater speeds. An increase in power by a factor of 5 to 10 would be required to operate the advanced system in the same way as the interim system. Actually, the threat might be somewhat different because fewer aircraft and missiles might be expected, it being quite costly for the enemy to achieve the increased speeds. In view of this, it might be plausible to consider maintaining the interim local-defense missile for use against the slower bomber attacks and to add to each missile station a few tracking radars and advanced missiles to be used against the advanced type of threat. For narrow-beam tracking radars which have a gain of 500 to 1000, only about 1 kw of average power would be required for each tracking radar.

VI. Advanced-Missile Problems

The performance requirements of the advanced missiles that have been discussed in previous sections of this report have led, in several instances, to specifications of component capability that go beyond today's technology, or that of the immediate future. The following paragraphs point out some of the specific technical obstacles and discuss possible avenues of attack. In estimating the dates that certain equipments may become available, RAND took a reasonably optimistic view, believing that these dates may be met by an appropriate concentration of research, development, and "debugging" effort.

The major powerplant requirement is associated with the demand that a missile stand in the field for periods up to 6 months and that it then operate satisfactorily on a moment's notice. It is believed that a realistic development for a storable motor, together with its associated fuel lines, valves, pumps, and fuel tanks, is an urgent necessity because the economic practicality of a missile system depends largely on achieving this type of operation. The main

effort is felt to be required (1) in overcoming nitric acid corrosion of lines, tanks, and valves, (2) in obtaining reliable nitric acid and JP-3 ignition systems, and (3) in reducing atmospheric deterioration of electrical and plumbing systems. The use of aluminum tanks and of new-type plastics (such as Kel-F) for seals and liners gives some promise of successfully handling nitric acid. Some hot-plate ignition systems, and some which use an initial injection of hypergolic fuel,[15] have been experimentally successful. RAND feels that the stand-by and atmospheric-resistance properties of the powerplant can be solved if the proper recognition is given to this problem during each misssile's development.

A material is required for radomes which will have satisfactory strength and dielectric properties up to about 1300°R. Further, it is necessary to find designs for radomes having thickness, laminations, shape, etc., which will permit a 20° to 30° seeker field of view without serious radar distortion. The generalized area-defense missile (see Chap. 8) and the advanced generalized local-defense missile (see Chap. 9) each require more advanced radomes than may be available in the near future. Current work on ceramic radome materials[16] indicates that operation at the specified temperature of 1300°R can be met. If radome research effort is expanded, a solution of the design problems should be possible within the next few years.

A dual-thrust motor is desirable for the advanced generalized local-defense missile to avoid problems associated with droppable boosters and their disposal in densely populated regions. Further, significantly lower skin and radome temperatures are encountered when this device is used. The maintenance of missiles is also aided, since only one-half the number of motors and fuel lines need be maintained.

Radar seeker power and maintenance condition represent parameters which greatly influence the basic cost of any missile system. The radar powers believed to be required are not considered to be especially prohibitive if the "maintenance degradation factor" (which has been taken from past experience) is not included. As a consequence, this parameter exercised considerable influence in the radar costs and weights used in the missile-system analyses, and any improvement would directly assist in the satisfactory accomplishment of missile-system

[15] For example, hydrazine hydrate, which is spontaneously combustible when mixed with nitric acid.

goals. The special case of the advanced area-defense missile required such a high degree of radar seeker performance that it is felt that the maintenance degradation factor must be greatly reduced (as compared with past experience) before such a missile will be feasible as an operational weapon.

Large fragmenting and blast-pellet warheads appeared quite promising, and the preferred missile designs of RAND's study used these warheads. The lack of firm data on these warheads, however, is a handicap in missile or rocket design and must be overcome if the most effective weapons are to be obtained. It is felt to be necessary to increase research and development in this field, particularly on the following aspects:

1. The vulnerability of modern aircraft and offensive missile components (such as turbojet or rocket engines, radar bombing systems, atomic bombs, and fuel lines) to fragments should be determined. This information is particularly necessary in the 10,000- to 20,000-fps fragment-velocity region.
2. The effect of altitude and initial velocity on the efficacy of blast and blast-pellet warheads, with respect to the above-listed components, should be determined.
3. The development of large warheads utilizing *combinations* of fragment and blast-pellet effects to achieve a high kill probability against both aircraft and offensive missiles should also be undertaken.

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APPENDIX I
OUTLINE OF PART II

Part II of this report on RAND's Air Defense Study is now being prepared. It will describe the synthesis work in which the equipment performance and the cost figures were interrelated in finding over-all defense effectiveness. The theoretical and mathematical background of the study, and the short cuts which were taken to avoid overcomplexity in the calculations, will be set forth. The numerical results will be discussed in relation to the corresponding qualitative arguments, as a background for the conclusions which were drawn. The proposed contents of Part II are presented below.

AIR DEFENSE STUDY

PART II

18. Discussion and Conclusions
Defense in 1953
Defense in 1955
Defense in 1957
Defense in 1959